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Contributions to the Genesis and Progress of ICF

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Pioneers of ICF

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Chapter for book, *Pioneers of ICF*

Contributions to the Genesis and Progress of ICF

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Inertial confinement fusion (ICF) has progressed from the detonation of large-scale fusion explosions initiated by atomic bombs in the early 1950s to final preparations for initiating small-scale fusion explosions with giant lasers. The next major step after ignition will be development of high performance targets that can be initiated with much smaller, lower cost lasers. In the 21st century and beyond, ICF's grand challenge is to develop practical power plants that generate low cost, clean, inexhaustible fusion energy.

In this chapter, I first describe the origin in 1960-61 of ICF target concepts, early speculations on laser driven "Thermonuclear Engines" for power production and rocket propulsion, and encouraging large-scale nuclear explosive experiments conducted in 1962. Next, I recall the 40-year, multi-billion dollar ignition campaign—to develop a matched combination of sufficiently high-performance implosion lasers and sufficiently stable targets capable of igniting small fusion explosions. I conclude with brief comments on the NIF ignition campaign and very high-performance targets, and speculations on ICF's potential in a centuries-long Darwinian competition of future energy systems.

My perspectives in this chapter are those of a nuclear explosive designer, optimistic proponent of ICF energy, and Livermore Laboratory leader. The perspectives of Livermore's post 1970 laser experts and builders, and laser fusion experimentalists are provided in a chapter written by John Holzrichter, a leading scientist and leader in Livermore's second generation laser fusion program. In a third chapter, Ray Kidder, a theoretical physicist and early laser fusion pioneer, provides his perspectives including the history of the first generation laser fusion program he led from 1962-1972.

A brief chronology of ICF progress at Livermore provides an outline of this chapter.

1942-60	Pre-1960 period—ICF's H-bomb roots at Los Alamos Livermore Lab founded (1952)—focus on advanced TN explosives Plowshare ICF power plant scheme
1960-61	Scheme for initiation of ICF without A-bomb Early indirect-drive ICF target concepts Low cost "bare-drop" targets; pulse shaping Speculations on laser-driven "Thermonuclear Engines" Early large-scale nuclear experiments
1962-72	**First laser fusion program** (See Kidder chapter)
1969ff	LASNEX target design code development Direct-drive exploding pusher targets and high performance bare-drop targets
1971ff	Declassification of ICF begins
1972-92	**Second-generation laser fusion program** (see Holzrichter chapter)
1974	Exploding pusher experiments—TN neutrons diagnosed
1976ff	Indirectly driven targets experimentally demonstrated
1977-82	Ten KJ Shiva laser/experiments
1976ff	Heavy ion fusion target designs
1979	Shiva-driven target implodes DT to 100-times liquid density; plasma physics barrier; short wavelength laser requirement
1977-87	Halite underground nuclear experiments (parallel Los Alamos Centurion experiments)
1985-95	Thirty KJ short wavelength Nova laser/experiments

1992ff	**Third-generation ICF program** Nuclear testing ends NIF proposal—" Key Decision Zero" by DOE
1994ff	Fast-ignitor laser and high gain target designs proposed
1997	Final DOE approval of NIF, and beginning of construction
2002ff	Very high-performance target designs proposed
2010ff	Planned NIF ignition campaign Development of very high performance targets

Early Development of ICF Concepts, 1942-1962
Creating a Possible Dream?

In 1942, J. Robert Oppenheimer, Edward Teller, Hans Bethe and other scientists met at the University of California in Berkeley and considered Enrico Fermi's 1941 question: Can an atomic bomb explosion ignite a "Super," a thermonuclear explosion of deuterium (1,2)? At the temperatures of an A-bomb explosion, fusion of liquid deuterium occurs in a fraction of a micro-second, more than twenty orders of magnitude faster than the proton fusion and carbon cycle processes that power the sun and stars on billion-year time scales.

Beginning in 1943 at Los Alamos, Teller developed a liquid density Super scheme (1, 2). However, late 1940s' calculations by Fermi, Stanislaw Ulam, John von Neumann, and others indicated an uncompressed Super is not practical.

In early 1951, Teller and Ulam proposed two-stage compressed Supers. Teller advocated radiation implosion coupling of the two stages (1,2). In a radiation implosion, an atomic bomb primary and a separate thermonuclear secondary are enclosed by a radiation case. A giant pulse of thermal X-ray energy radiated from the high-temperature primary explosion is channeled by the

radiation case to implode the secondary. The implosion enables efficient TN burn by reducing the fusion burn time relative to the inertial confinement time and the radiative cooling time.[1]

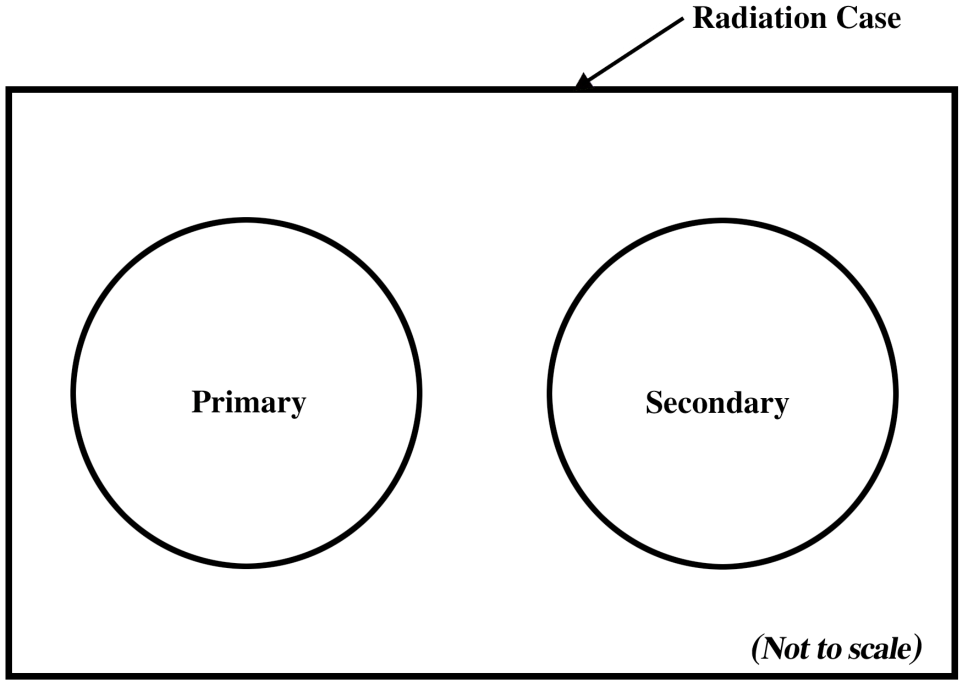

Figure 1. Teller's Radiation Implosion H–Bomb Scheme

After a successful radiation imploded deuterium-tritium (DT) ignition experiment in 1951, Los Alamos detonated a large-scale radiation-imploded TN explosion of deuterium in 1952. This 10-

[1] For example, a spherical implosion increases the specific burn rate faster than the inertial confinement time decreases. Specific burn rate is proportional to density, which is inversely proportional to the cube of the radius. Inertial confinement time is proportional to the radius. At constant temperature, total burn-up increases with rate x time, which is inversely proportional to the square of the radius.

megaton-yield experimental device known as MIKE demonstrated A-bomb initiated inertial confinement fusion (1,2).

Livermore

A few months before the MIKE explosion, the new Livermore Laboratory opened. Founded by Ernest O. Lawrence and Teller, Livermore focused on developing advanced TN explosives. A magnetically confined fusion energy program and other small programs were also initiated.

Figure 2. E.O. Lawrence and Edward Teller, Livermore Laboratory co-founders

Livermore acquired the fastest supercomputers and developed powerful weapons design codes. Theory developed at Los Alamos, Livermore, Princeton, the Rand Corporation, and elsewhere was incorporated into these codes. Results of nuclear test diagnostics were analyzed and used to improve codes and theory.

Within ten years, successive generations of more powerful computers and codes helped Livermore to become a leader in the development of TN explosives.

I was introduced to Teller's radiation implosion scheme in the summer of 1955, after I left Columbia University Physics Graduate School to accept a position in Livermore's Thermonuclear Explosives Design Division. I learned that matter can be highly compressed when subjected to the enormous pressures generated by a nuclear explosion, and that high densities are essential for practical TN explosives.

As a 24-year-old assistant to Harold Brown, the 26-year-old TN Design Division Leader, I studied nuclear explosives and weapons design code development and use.

Large-scale ICF power production

In 1957, Brown asked me to help evaluate the feasibility of producing commercial electric power by periodically exploding half-megaton yield H-bombs in a one-thousand foot diameter, steam-filled cavity excavated in a mountain. This large-scale ICF scheme was part of Teller's Plowshare program to develop peaceful uses of nuclear explosives (1). The commercial value of hundreds of kilotons of electrical energy is enough to pay the costs of fabrication, materials, operations, and capital. However, the large-scale cavity had an uncertain lifetime. Most important, there did not seem to be an economic advantage over fission and projected magnetically confined fusion power plants. A significant economic advantage would be necessary for ICF to overtake fission reactors and MFE. To achieve an economic advantage, I focused on reducing the size and cost of the cavity and on eliminating the A-bomb.

Is a large expensive cavity necessary? To calculate blast effects of confined nuclear explosions, I developed an elastic-plastic-fracture hydrodynamic explosion code (stresses and strains were tensors) (3). I realized that because the explosive impulse is proportional to the square root of mass the explosive impulse of a small mass TN explosion can be contained in a relatively small manmade explosion chamber—if the wall is shielded from

neutrons, X-rays, and hot plasma by a sufficiently large mass of unvaporized materials.[2]

Could very small DT burning fusion explosions be ignited without an A-bomb? (DT burns 100 times faster than D). In the late 1950s, John Foster, Fission Weapons Design Division Leader, invited me to attend meetings of his special group focused on how to ignite DT fusion explosions without use of an A-bomb. Physicists Ray Kidder, Jim Shearer and Jim Wilson were members of this group. Kidder developed useful approximations to the conditions for ignition of a small DT mass confined by a pusher (a dense metal shell). [3]

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[2] Energy times mass is proportional to momentum squared. Nuclear energy densities exceed chemical energy densities by more than a million fold. Hence, a nuclear explosive impulse may be reduced up to a thousand fold compared to that of an equal yield chemical explosive. In addition, 80% of the DT fusion energy is radiated as 14 MeV neutrons.

[3] Many physical processes are significant, including the range of the 3.6 MeV alpha particles, thermal electron coupling from the DT to the metal shell, the DT burn rate, the inertial confinement time, and the ion-electron coupling time.

Figure 3. John Foster and Harold Brown, fission and fusion explosive design leaders and early directors of Livermore Laboratory

I realized that a few hundred electron volt radiation temperature might suffice to implode and initiate a very small-scale fusion secondary. Radiation losses into a hohlraum wall decrease with more than the fourth power of the radiation temperature. With low radiation temperatures, excessive wall losses can be avoided even though the surface-to-volume ratio increases as the scale is decreased.

Non-nuclear primary, indirect drive scheme

Beginning in early 1960, I used the weapons programs' latest radiation implosion and TN burn codes to explore the feasibility of igniting a DT fusion micro-explosion with a tiny radiation implosion. I postulated that a "non-nuclear primary" could be invented to energize a tiny radiation implosion. I imagined several

candidates including a plasma jet, a hypervelocity pellet gun, and a pulsed charged particle beam.

In April 1960, I calculated the implosion of 10 mg of DT with an exploding foil energized by a high power electrical pulse. The DT did not achieve high enough densities and temperatures to ignite (4).

In May, I began to calculate small radiation implosions capable of igniting DT fusion micro-explosions in order to determine the energy and power requirements for a non-nuclear primary.

In June, I calculated the ignition and efficient burn of one milligram of DT. As I wrote (5): *"Radiation hydrodynamic calculations are presented which indicate the feasibility of . . .the radiation implosion of DT in amounts as small as 1 mg to runaway burn conditions . . . Sixty-seven percent of the DT burned in a calculation...In the implosion . . .."two-hundred forty volts temperature was maintained in the channel for one shake [10^{-8} seconds]. The total energy added was $6x10^6$ joules. It appears that only about $3x10^6$ joules was actually needed (the source was left on too long)" . . .* The input power was a few hundred terawatts. The fusion yield was 50 MJ, corresponding to a gain of ten. The yield was sufficient for weapons applications, but too small for energy applications.

I realized that in addition to a "non-nuclear primary," a second invention was required: a high gain fusion secondary that can generate a useful amount of fusion energy when ignited by a practical non-nuclear primary.

Today, the low temperature radiation implosion fusion microexplosion scheme is known as the "indirect-drive approach" and the "non-nuclear primary" is known as a "driver." Beginning in 2010, NIF will focus a multi-hundred-terawatt megajoule pulse of laser light to energize a few hundred electron volt temperature radiation implosion of a capsule containing a fraction of a milligram of DT. Targets have been designed to generate 30-100 MJ of fusion energy.

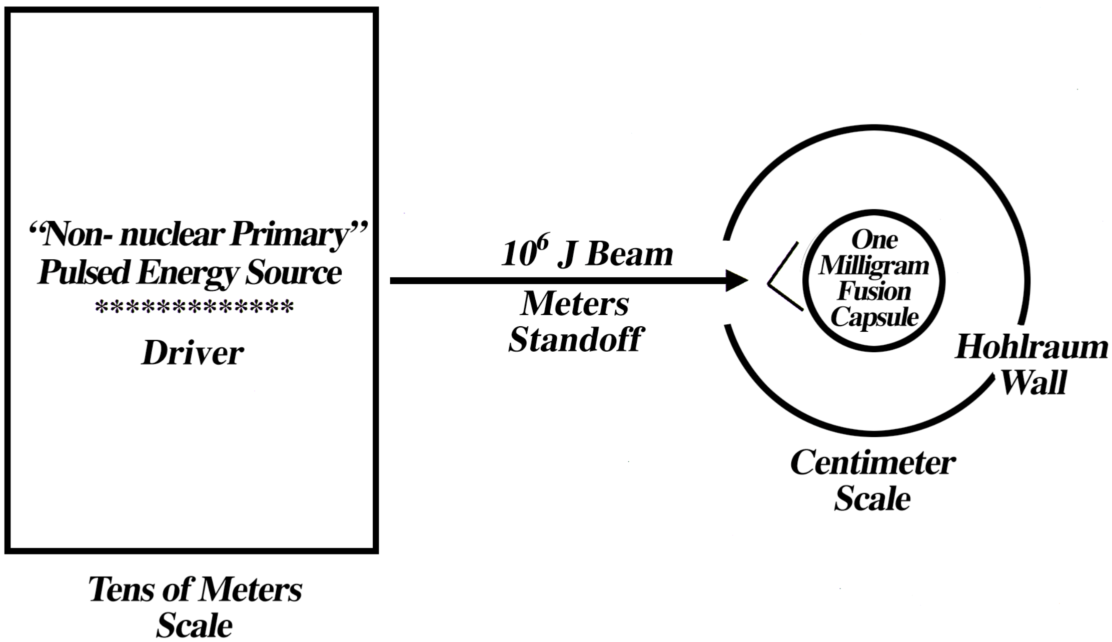

Figure 4. Non-nuclear primary/indirect drive scheme (1960)

<u>**Driver and Fusion Inventions**</u>

The driver may have kilometer dimensions but must concentrate energy in space and time to energize a tiny sub-centimeter-scale radiation implosion. For power production, the driver focusing mechanism must be separated a safe distance from the fusion explosion. The driver must ignite billions of micro-explosions in a 30-year power plant lifetime. The driver must have sufficiently low capital and operating costs so that the power plant can be economically competitive.

For weapons physics and effects applications, driver efficiency, repetition rate, and cost requirements are greatly relaxed. However, the value of an ignition facility to the weapons program must be comparable to the cost.

For power production applications, the fusion target must have a high enough gain (100 to 1000, depending on the driver cost) and low enough fabrication and material costs (less than a dollar). The driver energy required by the target must be small enough so that the driver cost is a small fraction of the total power plant cost. The tritium used in the capsule

is expensive and must be re-generated (e.g., by reacting DT neutrons with a Li^6 blanket).

Radiation Implosions — Megatons to Megajoules?

Over more than a nine-order-of-magnitude range in thermonuclear yield, from megatons to megajoules, there is apparently no competitor for radiation implosions. Why?

Figure 5. Teller with a full-scale model of a Soviet 100MT Weapon. The thumbnail on Teller's right hand is the size of ICF targets

The radiation implosion approach excels at small scales because it can partially control the physical processes that limit performance, including asymmetries and fluid instabilities.

Implosion symmetry is enhanced because the radiant energy absorbed in a thin layer of the high Z walls of the hohlraum is efficiently re-radiated multiple times and has a velocity a thousand times larger than the implosion velocity of a fusion capsule. Energy radiates from hot areas to cooler areas, rapidly equalizing temperatures.

Growth rates of fluid instabilities are reduced because kilovolt range thermal radiation from a few hundred eV temperature black body rapidly ablates the unstable interface in low atomic weight materials. Density gradients also reduce instability growth rates. In 1960, we understood that favorable density gradients are created, and that radiation transport effects reduce growth rate of fluid instabilities (suggested by Livermore physicist Chuck Leith). But we did not have a quantitative understanding.

Distortions and instabilities generated by energy concentration processes located in the driver are effectively decoupled from the spatially separate secondary implosion when the secondary is energized by black body radiation from the driver-heated hohlraum walls. Consequently, radiation coupled drivers and fusion capsules may both be operated near their stability limits to achieve maximum performance.

Driving pressures of several hundred megabars and implosion velocities of hundreds of kilometers/second can be generated by ablation with several hundred eV radiation temperatures. At these temperatures, material sound speeds are several hundred kilometers/second, comparable to the implosion velocities required to isentropically compress DT to more than one thousand times liquid density. One-thousand-fold compression of a sphere can reduce the required driver energy by nearly one-million-fold.

Although radiation imploded, my milligram capsule had stability limitations. The initial density of the DT was 0.01 g/cm^3. It

was enclosed by a very thin high density metal shell surrounded by a beryllium ablator. The initial average density of the capsule was sufficiently low so that the radiation temperature necessary to drive the implosion to ignition was only 240 eV. The DT imploded to several hundred times liquid density and ignited at a temperature of several KeV. However, the pusher was too thin to survive growth of fluid instabilities during implosion.

In 1961, my group leader, Peter Moulthrop; nuclear designer Ray Birkett; and I addressed the pusher fluid instability problem by separating the pusher from the ablator and moving the pusher inward to make it thicker.

In 1961-1962, Stirling Colgate, Ron Zabawski, Pete Moulthrop, Dave Hall, Ray Birkett, Jim Wilson, and other Livermore designers made calculations with weapons codes of the radiation implosion and ignition of small DT masses contained by pushers. Calculated gains were roughly one with input energies of 0.1 to several megajoules. These gains were sufficient for weapons applications, but far too small for power production.

In all these microfusion capsule designs, the pusher limited the gain because its mass was up to one hundred times larger than that of the DT. To achieve high gains (100 and greater), the pusher had to be eliminated and the implosion energy had to be minimized.

High efficiency fusion capsules

To minimize the implosion energy most of the DT must be near isentropically compressed to high densities. The Fermi energy of DT compressed one thousand fold is only one percent of the ignition energy, (i.e., the thermal energy at 10-kilovolt ignition temperature). The ignition energy is only one percent of the fusion energy at 30 percent burn-up. Consequently, the fusion energy generated can be 10^4 times larger than the Fermi energy of the compressed DT! The gain can be further increased by igniting a relatively small fraction of the DT mass in a hot spot near the center of spherical convergence. Fusion yields can then be amplified by TN propagation from the hot spot into a much larger mass of DT. Even with one percent efficient implosions, the energetics is extremely favorable.

I developed an ablatively driven spherical rocket implosion to compress DT to high densities without use of a pusher. A sustained ablatively driven implosion is made possible by use of a sustained driver input and a suitable ablator. Optimum pulse shapes make possible very high isentropic compression of most of the DT while igniting a central hot spot. The temperature of the hot spot is amplified by adjusting the pulse shape so that a strong shock is generated near zero radius, and by using a hollow target design containing low-density DT gas.

In a series of 1961 calculations, I explored the potential of strong pulse shaping. With near ideal pulse shapes, very high-gain, pusherless, near isentropic, low temperature radiation imploded fusion capsules that ignite propagating burn are feasible. For fusion power plant applications, these are necessary but not sufficient elements of the high gain fusion invention. Target cost is also a major problem.

The value of the energy generated by a gigajoule TN explosion is roughly a dollar. Precision-machined capsules (to minimize growth of fluid instabilities) may cost thousands of dollars. In late 1960, I realized that a near perfect liquid DT droplet that can be manufactured with the equivalent of an "eye-dropper" might serve as an ICF target. I made supercomputer calculations of the radiation implosion of a "bare drop" of DT. The outer DT served as an ablator. By optimizing the temporal pulse shape, a high-density implosion with multi-kilovolt central temperatures was calculated. With a 10-MJ input energy and a peak hohlraum temperature of 400 eV, the DT core was imploded to densities of 1000 g/cm^3, and central temperatures of several keV were reached. I was amazed by this beautiful calculation.

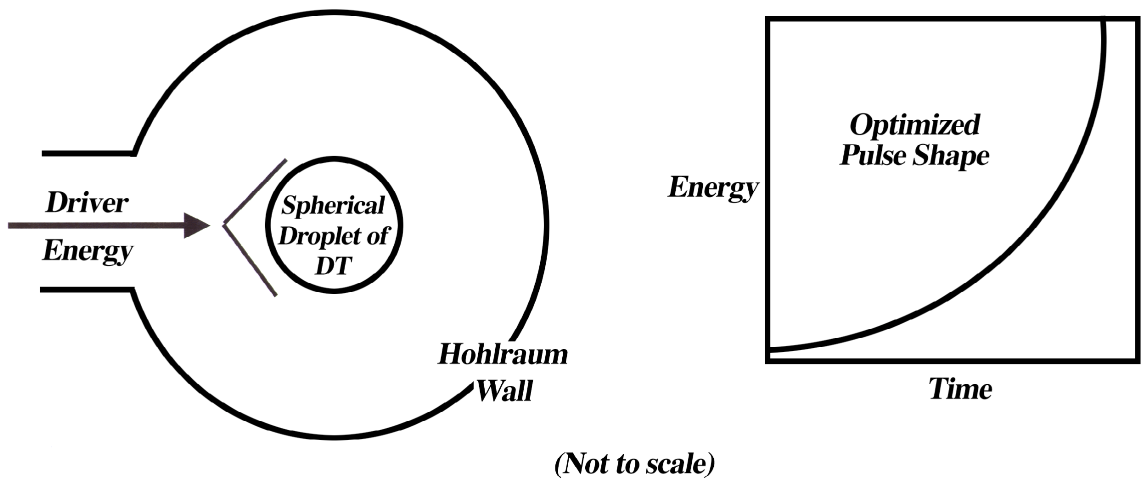

Figure 6. Bare Drop Target with Optimized Pulse Shape (1961)

Livermore's professional weapons designers regarded my tiny low-cost, high gain ICF target designs as science fiction. We joked about "Nuckolls' Nickel Novels" (referring to my prolific series of classified memos). Without nuclear tests, these radical target designs could not be taken seriously. Fortunately, my efforts were strongly supported by Carl Haussmann, who succeeded Brown as TN Division Leader, and by Foster, who succeeded Brown as Livermore director in early 1960. (Brown was selected by President Kennedy to lead Department of Defense (DOD) Research and Engineering.)

__Lasers demonstrated__

In July 1960, Theodore Maiman at Hughes Research Laboratory announced the first successful laser experiments at a press conference.

We recognized that coherent laser light could be highly focused to heat a small mass of uncompressed DT to TN temperatures. We also knew that heating uncompressed DT to TN temperatures cannot achieve practical ICF[4]. Implosions that create high densities are the path to ICF.

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[4] The smallest mass of inertially confined liquid density DT that can be ignited is a few grams (corresponding to a density radius product of $0.3 g/cm^2$ in a sphere). More than a GJ is required to ignite this mass, and the resulting

In spring and summer 1961, we realized that giant lasers might someday drive radiation implosions of milligrams of DT and might be suitable drivers for an ICF power plant. In principle, a high power laser pulse could be focused several meters from the wall of an explosion chamber through a tiny hole in a small hohlraum to generate radiation temperatures of several hundred electron volts. The laser's stand-off capability would enable protection of the laser and focusing optics from neutrons, X-rays, and hot plasma generated by the DT explosion.

Stirling Colgate, who shared an office with me, analyzed the heating of a tiny hohlraum by intense laser light and estimated that several hundred eV radiation temperatures could be reached with lasers focused to more than 100 TW/cm^2. (6)

In September 1961, I proposed to Livermore Director John Foster that the Laboratory explore a "THERMONUCLEAR ENGINE." In a memo to Foster, I wrote: "*The idea is. . . to make the fusion analog of the cyclic internal combustion engine. DT or D is burned in a series of tiny contained explosions. . . . A problem is how to implode the DT to burn conditions without a pusher . . . A LASER system would be particularly advantageous here, because the energy could then be easily transferred via light – from the walls of the chamber to the DT to make a pusherless implosion of a droplet of DT. . . calculations show that such an implosion and the subsequent tamperless burn is feasible for a droplet of DT weighing a few mg . . Possible applications for this engine are power production (Sherwood) or a thermonuclear rocket (fusion Rover).*" (7)

My highly speculative far-future TN Engine proposal seemed like science fiction—and was ill timed. Livermore was focusing all possible efforts on responding to high yield Soviet atmospheric nuclear tests (including a 57-megaton explosion). Our goals were to eliminate the potentially catastrophic first strike instability in nuclear deterrence and to search for technological surprises.

A low level of work on ICF continued. In an early 1962 memo Colgate described a radiation implosion calculation by Ron

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fusion yield would be approximately 100 tons. GJ drivers and 100-ton explosions are impractical for power production.

Zabawski of a target with two dense shells in which less than ten micrograms of DT is ignited, giving a gain of about one.

<u>Nuclear tests—"Dramatic Advances"</u>

In April 1962, the U. S. responded to the Soviet tests by launching an intensive nuclear test series. Livermore's advanced warheads achieved a major success—in an "Admiral's test" of the Polaris submarine launched ballistic missile. This Polaris weapons system addressed the first strike instability, by creating a secure second strike nuclear force.

Meanwhile, I focused on technological surprises. In April 1962, a few months before the scheduled end of the atmospheric test series, I proposed a nuclear test of a radical high-yield TN design so fantastic that my colleagues thought it was an April Fool's-day joke. In this radical design, a high-performance TN secondary was imploded with a highly optimized pulse.

Foster dispatched me to Washington to support approval of a nuclear test of my scheme. I was accompanied by Roland Herbst, a theoretical physicist and experienced weapons designer. I briefed AEC Chairman Glenn Seaborg, and my former boss, DOD's R&D leader Harold Brown. President Kennedy approved the nuclear test—the last experiment in the test series.

I was the lead nuclear designer—and this was my first nuclear test. Not nearly enough time or computer resources were available. Livermore's nuclear design experts believed success was impossible. Foster and Moulthrop were notable exceptions. I severely constrained the nuclear design to minimize calculations, to use parts that could be rapidly fabricated, and to avoid or overpower failure modes. Nuclear design, engineering, and fabrication were completed in two months. (Today, years would be required.) Invaluable assistance was provided by my sole assistant, Ron Theissen, a technician on assignment from the Computation Department. Several other designers volunteered to assist. Day and night, Ron and I punched IBM cards as inputs for hundreds of one dimensional calculations. Although the device was an extreme design, enough computing time was available for only a few simple two dimensional calculations.

Figure 7. Group leader Pete Moulthrop (center) and John Nuckolls at a TN Design Division Party

On a pre-dawn morning in early July 1962, I observed the multi-megaton yield "Pamlico" explosion of my device from a Christmas Island beach at the Joint Task Force Eight Pacific nuclear test site. We wrapped in white sheets to avoid thermal radiation and wore dark goggles. Fifty miles distant, a B52 had dropped the parachute retarded nuclear device. Suddenly, we were stunned and dazzled by the multi-megaton pulse of intense light and heat radiated from the three-kilometer fireball. Night became day. The giant mushroom cloud surged upward and stabilized at an altitude of 80,000 feet. The Soviet spy ship was steaming over the horizon.

Foster sent the director's car to meet me at the San Francisco airport. Later, he hosted a dinner/musical celebration at San Francisco's Palace Hotel.

My colleagues were amazed at my beginner's luck and counseled me "quit while you are ahead." But, I resonated with the creative optimism of Lawrence and Teller. I had no fear of failure. Foster's rule was if you don't fail half the time, you aren't trying hard enough. His dynamic spirit inspired Livermore. "You can excel! I want to run so fast anything the Soviets build will be obsolete."

In July, the Soviet and U. S. governments decided to extend the test series until October 31. Both nations conducted spectacular high altitude nuclear tests that summer.

In August and September, Ron and I worked day and night to design an even more radical nuclear device. We further optimized the pulse shape to achieve practically isentropic fuel compression. On October 1, this device was exploded in the "Androscroggin" nuclear test conducted in the Johnson Island area of the Pacific. A small percent of the calculated yield was generated—a fizzle!? Everyone believed I had "snatched defeat from the jaws of victory."

With less than a month before the test series ended, I reviewed early diagnostic data, recognized my design error, and devised a fix which could be rapidly fabricated. Shortly thereafter, a highly successful subsequent test was conducted. Performance increased two-fold over the July test.

The October 30 *New York Times* reported, "*According to officials closely connected with the weapons program, dramatic advances were achieved in devices hurriedly prepared by scientists at the … Weapons Laboratory in Livermore, California."*

My experiments provided credibility as a TN designer, and increased confidence in radical TN designs.

<u>Next steps</u>

After atmospheric nuclear testing ended, Foster accelerated the underground nuclear test program to develop advanced nuclear explosives. We attempted the first precursors of the Halite-Centurion experiments conducted in the 1970s and 1980s. However, fabrication proved to be extremely difficult. New high precision machines were required. Initial nuclear experiments were not successful.

After Kidder reported on his meeting with Maiman (at Hughes Labs) to discuss the future of high power lasers, Foster decided that possible weapons applications justified launching a laser fusion program. He appointed Ray Kidder to lead this program.

I had a dream of Thermonuclear Engines—but was it a possible dream? We did not know what laser size, target gains or reductions in fluid instability growth rates and implosion asymmetries were necessary or possible. Of plasma instabilities, we knew nothing (and had a lot to learn). Our computers and design codes were not adequate. Costs of lasers, target fabrication, and reaction chambers were not predictable. Fortunately, ICF was funded by the weapons program for weapons physics applications.

Laser Fusion Program, 1962-1972
The Awakening

During the 1963-68 period, I focused on exploring advanced TN explosives for strategic, missile defense, battlefield and Plowshare applications. And, I waited for Ray Kidder's program to develop implosion lasers so that experiments on laser-matter interaction and targets could be conducted. (See Ray Kidder's chapter for a history of this program.)

In 1964, Kidder calculated a low-gain target energized by direct laser radiation. Spherically symmetric laser light was absorbed by a hydrogen ablator to drive the implosion of DT contained in a dense metal pusher. High gains were precluded by use of the pusher. Ignition was calculated using somewhat less than a megajoule of laser light. (See Kidder's chapter) Plasma physics and implosion symmetry issues were not addressed.

Kidder addressed the use of high-power lasers to generate high temperatures and pressures in a 1968 publication (8).

In 1966, J. Diaber, A. Hertzberg, and C. Witcliff (9) proposed laser driven implosions.

In 1968 experiments, Professor Nikolai Basov and others used a high intensity laser pulse to heat uncompressed fusion fuel. Fusion neutrons were detected. I expected the Soviets would build lasers to conduct implosion experiments. This proved to be correct (10).

In 1969, Professor Mosehe Lubin, leader of the University of Rochester laser fusion program, and John Dawson, professor of Plasma Physics at Princeton, visited LLNL to discuss laser fusion on a classified basis. Each had a target scheme. Neither scheme imploded DT to high densities. I briefly mentioned my classified 1960-62 concepts and calculations. Later in 1971, the paper (11) by Kruer and Dawson on laser-driven plasma instabilities revealed serious problems for target designers. A 1971 *Scientific American* article by Lubin focused attention on the possibility of ICF power production.

In a late 1960s, I learned that at an AEC meeting on laser fusion, Professor Keith Brueckner presented classified calculations of laser-driven implosions of hollow DT micro spheres. Kidder did not support Brueckner's proposal that the AEC explore commercial power applications of laser fusion[5]. Kip M. Segal and Brueckner formed KMS Fusion and applied for AEC funding to develop laser fusion energy applications.

Lawrence Award—a turning point

In 1969, my "contributions to the design of high efficiency thermonuclear devices, including clean explosives . . ." were cited in an E. O. Lawrence Award granted me by President Nixon and the U. S. Atomic Energy Commission. I used the influence created by this award to promote ICF.

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[5] After this meeting, I calculated Brueckner's target designs and learned that our weapons codes were much more pessimistic than Brueckner's code.

Livermore Director Michael May (who succeeded Foster in 1965) and Carl Haussmann (then Associate Director for Military Applications) arranged for me to address the AEC General Advisory Committee and the President's Scientific Advisory Committee.

In 1970, I proposed the AEC declassify our new calculations of a DT bare drop directly imploded by laser light. The AEC approved. This was a major contribution to the progress of ICF. The combined efforts of laboratories and researchers in many nations have contributed to the development of ICF energy applications.

Extraordinary Collaborators

Lowell Wood, a brilliant young protégé of Edward Teller, became a collaborator in 1969. Subsequently, Lowell made many outstanding contributions to the theory and development of ICF. Lowell also secured Teller's support. In the early 1980s, Lowell received an E. O. Lawrence Award for his outstanding contributions in many areas including work on nuclear explosive pumped X-ray lasers. Another brilliant young collaborator, George Zimmerman, initiated the development of successive generations of LASNEX—the leading ICF code, which made possible greatly accelerated progress. In the 1980s, George received an E. O. Lawrence Award. Other outstanding collaborators included Ron Theissen and Yuli Pan who worked closely with me to rapidly accelerate progress in the design of advanced targets.

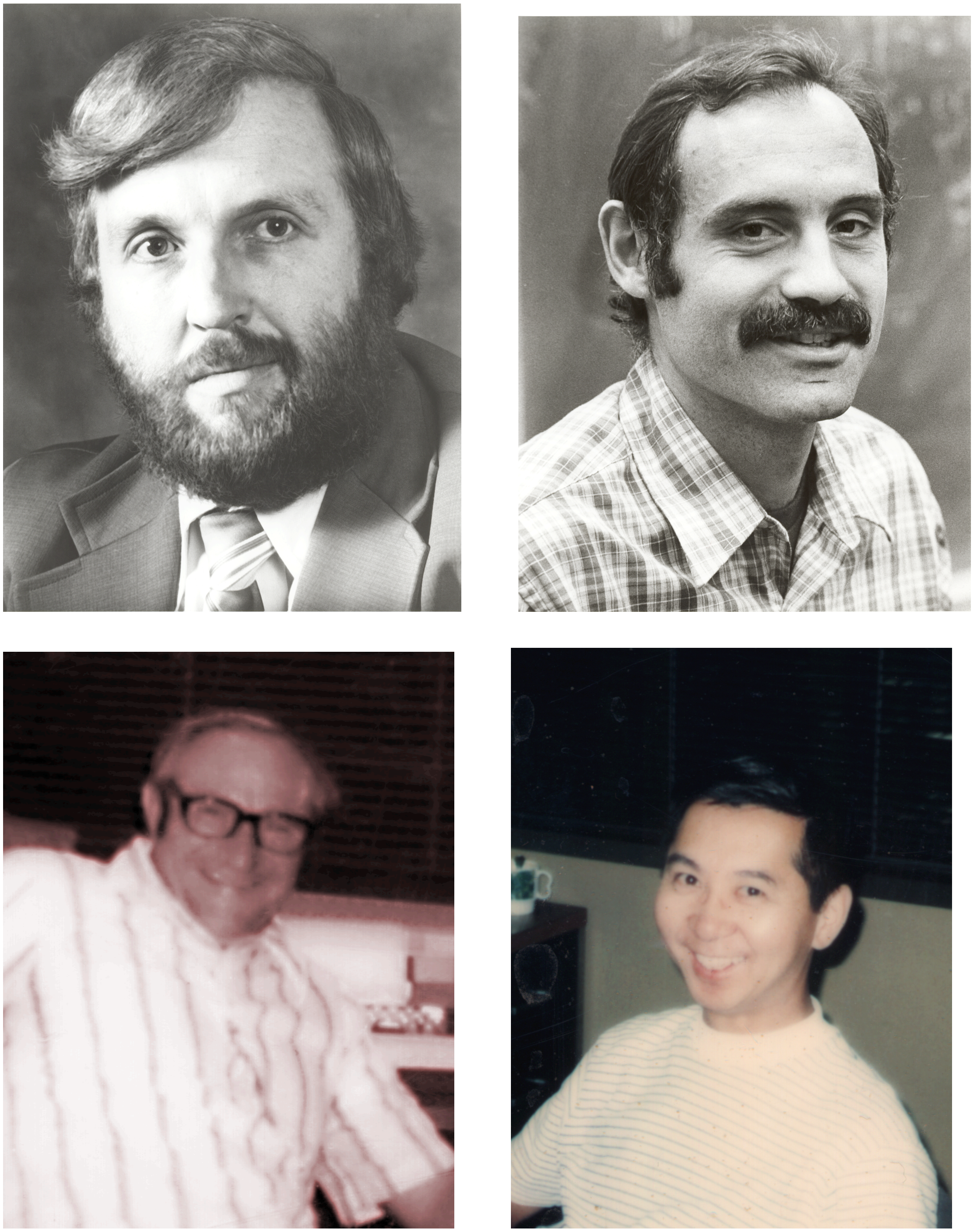

Figure 8. Collaborators (clockwise from top left): Lowell Wood, George Zimmerman, Ron Theissen and Yuli Pan.

LASNEX—Zimmerman's ICF code

The LASNEX code used a two-spatial dimension finite difference scheme to simulate a variety of physical processes including hydrodynamics, energy transport, and coupling between thermal ions and multi-group electrons; thermal radiation generation and absorption via bremsstrahlung and a variety of non-linear processes; laser light transport and absorption and thermonuclear burn, including non-local transport of charged fusion reaction products. In 1969-70 with 10-fold more powerful computers than in 1960, two-dimensional distortions of implosions were calculated.

LASNEX was used in the late 1960s and in the 1970s to calculate laser-heated electron imploded bare drop targets, and microscopic exploding pusher targets (low density DT gas contained in glass micro-balloons). Beginning in the 1970s, LASNEX was also used to understand detailed diagnostic results of laser-matter and laser fusion experiments. In the 1990s and in this decade, LASNEX has been used to design ignition targets for NIF.

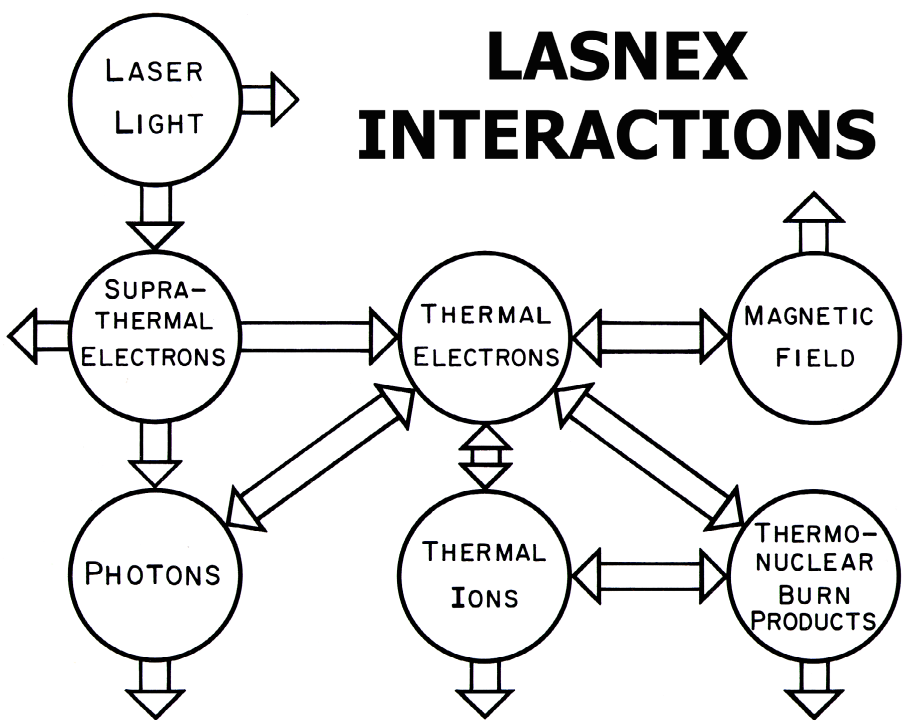

Figure 9. LASNEX Target Design Code

AEC Evaluation of ICF

In 1971, the AEC and the PSAC requested a new evaluation of laser fusion by the weapons labs. Director May and Associate Director Haussmann asked me to represent Livermore

At meetings with the AEC Commissioners in late '71, and with the PSAC in early '72, I discussed radiation implosion and direct drive concepts, and results of relevant weapons experiments. I estimated that several megajoules of laser energy would be sufficient to drive a high-gain radiation implosion, and that a high risk alternative might be provided by directly driven targets energized by 100 kilojoule class lasers. I predicted ICF would be valuable for weapons physics applications and would ultimately provide a fusion energy source. To bound our large uncertainty in the state of the Russian program, I speculated on what might be accomplished if everything worked as predicted and funding were rapidly increased. I recommended an evaluation of suggestions that mobile explosive pumped lasers might be able to ignite fusion explosions. A year later in January 30, 1973, *The New York Times* reported "AEC to Focus on Laser Bomb."

Kilojoule Impetus

We learned that Brueckner, scientific leader of the KMSF effort, had recently estimated that a kilojoule energy laser could generate a kilojoule of fusion energy. Our-back-of-the-envelope estimates agreed with Brueckner's. We ran a series of spherically symmetric LASNEX calculations to find the performance limits of directly imploded, bare drops of DT. In these ideal spherical calculations, a kilojoule of absorbed laser energy having an ideal temporal pulse shape and a short enough laser wavelength to avoid non-Maxwellian effects, generated up to a kilojoule of fusion energy from a directly driven/electron-imploded, bare-drop target design. A final strong shock was used to achieve ignition. This result was very sensitive to incompletely understood plasma and fluid instabilities and to laser limitations (wavelength, peak power, uniformity of irradiation, etc.).

Results of these calculations provided a strong impetus for building a 10 kilojoule laser, and exploring the feasibility of a 100 KJ laser.

LASNEX calculations of much larger, less sensitive targets predicted that a megajoule or more of absorbed laser energy would be needed to achieve one-hundred-fold target gains required for ICF power plants.

Directly-driven Electron-coupled Targets

Our laser-heated electron implosion target designs that addressed symmetry and fluid stability issues were developed in 1970. Imploding material is shielded from laser irradiation imperfections by electron transport processes, including thermal electron scattering in a substantial, low-density atmosphere initially generated by exploding an outer shell and sustained by material ablated from the imploding capsule. The initial configuration of the target and the temporal laser pulse shape were adjusted so that the critical density radius at which the laser energy is absorbed is at least twice as large as the radius of the ablation front at the dense imploding shell. Symmetry is enhanced because there are many electron-scattering, mean-free paths between the radius at which laser light is absorbed and the radius of ablation. Stability is enhanced by ablation and density gradients. But stabilization is not as strong as in indirect-drive implosions where much more material is ablated by energetic thermal photons radiated from the hohlraum wall.

Microscopic Exploding Pusher Targets

In exploding pusher targets containing low density DT gas, energetic non-Maxwellian electrons (generated by interaction of matter with a pulse of intense laser light) are transiently confined electrostatically while fast ions began to escape into the surrounding vacuum. Thermal electrons are strongly heated. Sudden strong heating by non-thermal and thermal electrons causes the glass pusher to explode at velocities of hundreds of kilometers/second. Inward moving ions from the exploding pusher collide with DT ions compressing the fuel to ~1 g/cm^3 and heating the DT ions to kilovolt temperatures.

I proposed laser-imploded microscopic exploding pusher targets in 1969 in response to a challenge by Teller. Teller made the achievement of predictable laser-driven implosion experiments a condition for his support of an accelerated laser fusion program. In 1970, we attempted to use the short-pulse, single-beam glass laser at Sandia Albuquerque to implode fifty-micron diameter, AL coated, LiD micro sphere, exploding pusher targets I designed. These targets were fabricated at Livermore. However, no neutrons were observed. Performance was marginal because no tritium was used and the ratio of the Al and LiD densities was not very large. Also, the target could have been evaporated by a tiny laser prepulse.

Subsequently, much higher performance exploding pusher targets containing low density DT fuel were fabricated at Livermore and elsewhere by creating large numbers of thin-walled glass micro-balloons in a heated drop tower. Chuck Hendricks led the target fabrication program. After sorting by size, wall thickness, etc., hot high pressure DT gas was diffused through the thin glass shells of the micro-balloons to achieve the desired DT density. Cooling trapped the DT inside the micro-balloons. Glass micro-balloons were suggested by Stirling Colgate in 1965 to contain high pressure hydrogen fuel for rockets.

Ten Kilojoule Laser Proposal—Great Debate on Path Forward

In 1971-72, Lowell and I proposed priority construction of a high-power, 10-kilojoule laser capable of generating near-ideal pulse shapes and driving high quality spherical implosions. We proposed flexible one-micron wavelength solid state lasers over efficient, ten-micron wavelength CO_2 gas lasers. (High-power $C0_2$ lasers were developed and used by the Los Alamos ICF program.) With short enough wavelengths, efficient absorption of laser light could be achieved in both directly driven and radiation implosions, and plasma instabilities would be limited. If necessary, one-micron laser light could be converted to shorter wavelengths.

Reports that Soviet laboratories had achieved multi-beam laser-driven implosions gave strong impetus to our aggressive proposal. However, Ray Kidder was a strong “go slow” proponent. Initially, he was supported by Teller. Kidder and Teller pointed to our inadequate understanding of high-power lasers and of the interaction of intense laser light with matter. Material damage and

optical distortions due to non-linear effects were potentially serious problems. Plasma physicists suggested the possibility of anomalous reflection of laser light and hot electron generation due to plasma instabilities driven by intense laser light focused into low-density plasmas. Hot electrons would preheat targets and would not couple efficiently to the target implosion. Kidder also argued that compression might be useless if the compression efficiency declined rapidly as the density increased.

Lowell and I argued that large-scale experiments were needed. We suggested that some plasma instabilities might be used to absorb laser light. Teller strongly advised that instabilities are likely to be damaging and should be avoided. We agreed that short wavelength lasers should be developed to increase absorption.

Cost was a decisive factor. Over a period of ten years, the AEC-funded laser fusion program would cost several times as much as a 10 KJ laser. Better to build the laser and learn as fast as possible.

Associate Director Carl Haussmann strongly supported an aggressive laser fusion program. Carl judged that weapons physics applications and the future potential of lasers (e.g., for isotope separation and military and commercial applications) provided a strong basis for launching an aggressive program to build large lasers.

The laboratory discussed and rejected the purchase of commercially available French solid-state lasers. Better to develop and build much higher performance next generation lasers.

Director Mike May and his 1972 successor, Roger Batzel, decided to launch an aggressive program to build the 10KJ SHIVA laser. Teller supported this decision.

Declassification/Early Publications

The Atomic Energy Act provides for declassification of some weapons information useful for peaceful applications of atomic energy. I believed that declassification of the directly driven, bare drop scheme was feasible. In a presentation to the AEC Classification Committee chaired by Charles Marshall, I stressed the following: a hohlraum is not used; a simple, bare spherical droplet

does not reveal classified weapons design information; and classified manufacturing techniques are not revealed—an "eye dropper" may be used to create a near-perfect droplet smoothed and spherized by surface tension. The AEC approved most of this proposed ICF declassification.

1972's IQEC

The great awakening of the scientific community began at the May 1972 International Quantum Electronics Conference in Montreal. Teller led with an invited talk on the importance of global scientific cooperation on laser fusion. He also discussed laser energized Thermonuclear Engines. I led a series of four coordinated invited talks with Wood, Thiessen, and Zimmerman on ICF target theory, concepts, and calculations recently declassified by the AEC (12, 13, 14, 15).

Teller gave a second presentation on a laser fusion powered rocket to Mars designed by Rod Hyde (16).

Basov led a delegation of Soviet scientists who discussed ICF target designs with thin high-density pushers, similar to capsules used in my 1960 calculations. Our calculations predicted these targets would be severely degraded by fluid instabilities. Russian scientists also emphasized hybrid fission-fusion power plants.

After the IQEC meeting, the AEC declassified spark ignition of TN propagation. This made possible our September 1972 *Nature* paper.

Figure 10. Lowell Wood and John Nuckolls at the 1972 IQEC Press Conference

In the September 1972 issue of ***Nature*** (17), we published the theory, target design, and LASNEX calculations declassified by the AEC. A directly driven electron coupled bare drop was ablatively imploded near-isentropically to ten thousand times liquid density by an optimized pulse shape, ignited in a central hot spot, and TN burn was propagated outward to ignite cold, dense DT fuel surrounding the hot spot. A final shock was used to achieve extremely high velocities that ignite a near isochoric density distribution.

Although hollow target calculations were still classified, we were allowed to note that use of hollow targets would reduce the required peak laser power, and might enable use of longer laser wavelengths. Los Alamos published calculations of hollow targets in 1973-1974 (18).

In 1973, I presented an expanded version of the declassified material at a Renneslear meeting (19).

In 1974, we presented a paper on hollow targets (20). In this paper, we calculated the use of an impulsive picket fence approximation to a smooth ideal pulse shape in order to reduce growth of fluid instabilities for a given implosion velocity and DT entropy.

AEC Approval of Ten-Kilojoule Laser Initiative

To lead a second generation laser fusion program, including development and construction of a 10KJ laser, Haussmann, Lowell and I strongly recommended that John Emmett be recruited. Director Batzel approved our recommendation. Emmett was an outstanding young scientist and solid state laser builder at the Naval Research Laboratory. We met him at a meeting of the President's Scientific Advisory Committee. He was a strong advocate of ICF in U. S. government circles. Haussmann personally recruited Emmett, and also Bill Krupke, who became Emmett's deputy.

In 1972-1973, I accompanied Haussmann to AEC headquarters and gave a briefing to AEC Chairman Jim Schlesinger on ICF and the case for a 10KJ laser. He approved Livermore's proposal. Bob Hirsch, who directed the AEC fusion energy program, provided strong support.

Second Generation Livermore ICF Program, 1972-1992
Full Speed Ahead—The Plasma Physics Barrier

In the early 1970s, Director Roger Batzel launched an aggressive second-generation laser fusion program. Carl Haussmann led this program until John Emmett recruited his management team. Although we faced major risks and unknowns, the prevailing spirit was "damn the torpedoes, full speed ahead."

Figure 11. Carl Haussmann and John Emmett, "prime movers" of Livermore's Second Generation laser fusion program

After the oil supply disruption of 1973, the United States launched a major energy independence initiative, which included increased funding to develop fusion energy. The magnetic mirror program at Livermore was accelerated and a Tokamak program was launched at Princeton.

Goals of Livermore's ICF program were expanded: "to determine the scientific feasibility of ICF by lasers, and to apply this

technology to weapons and commercial power applications." Although significant energy program funding was not provided, weapons program funding of ICF increased in the seventies to more than 100M$/year while the Shiva laser was constructed and utilized and the Nova laser was developed.

In high density experiments conducted with Shiva in the late seventies, we crashed into a disastrous plasma physics barrier. Nova plans were modified to provide a short wavelength capability. We learned that to achieve ignition, a third generation Livermore program with a short wavelength megajoule scale laser would be needed—a third generation program that would dwarf the second generation program, just as the second generation program dwarfed the first. Major breakthroughs in lasers, targets, and politics would be required.

Building A Second Generation Program

Emmett recruited an outstanding team at Livermore —including Bill Krupke, John Holzrichter, John Trenholme, Walt Sooy, Erik Storm, Hal Ahlstrom, Chuck Hendricks, Ken Manes, and many others. With great leadership, unmatched laser and experimental expertise, and strong laboratory engineering and technical support, Livermore's ICF program rapidly surpassed competitors (See Holzrichter's chapter). Emmett received an E. O. Lawrence Award in 1975 for his outstanding contributions.

X Division

Powerful scientific, computations, and target design capabilities are crucial to the success of ICF. As Associate Leader of the TN Design Division, I recruited many of the best and brightest young physicists from leading U. S. graduate schools and created an "X" Division, which included three groups: the LASNEX group led by George Zimmerman, the Plasma Physics group led by Bill Kruer, and the Target Design group led by John Lindl. By 1980, X Division included more than two dozen outstanding scientists. Many have been recognized with prestigious awards: George Zimmerman and John Lindl received Lawrence Awards and Teller Medals; Bill Kruer received the Maxwell Prize; Claire Max received a Lawrence Award; and Mordy Rosen, Steve Haan, Larry Suter, and Max Tabak received Teller Medals.

Figure 12. John Lindl, Bill Kruer, and George Zimmerman: X Division Group Leaders for Target Design, Plasma Physics and LASNEX respectively

Zimmerman's LASNEX code used successive generations of more powerful weapons program supercomputers, which provided one hundred-fold greater computing power in 1992 than in 1972. LASNEX capabilities rapidly expanded. Improvements included extensive Monte Carlo physics, laser-driven plasma physics approximations, advanced two-dimensional hydrodynamics, and energy transport. In parallel, Kruer and his group developed ZOHAR and other state-of-the-art collisionless plasma physics codes. (21, 22)

In a major change from traditions of the highly classified weapons program, "X" Division physicists published results of most of their work and were very active in the scientific community. I led this new openness by presenting invited and review talks at U. S. universities and scientific meetings, and at international scientific meetings. In a memorable talk at the California Institute of Technology physics colloquium, Feynman, Gell-Mann and other eminent scientists fired tough questions. At Cornell, Bethe led the questioning.

<u>**Short Wavelength? Indirect Drive?**</u>

Laser wavelength was a key issue. One micron wavelength light from Nd glass lasers might not suffice. Our 1972 *Nature* paper discussed use of short wavelength laser light to reduce adverse plasma physics effects. Emmett initiated development of a short

wavelength capability. By 1980, large-scale short wavelength capabilities became practical and were incorporated in the Novette and Nova lasers. University of Rochester scientists made important contributions to the development of these capabilities.

A second key issue was the configuration of Shiva's 20 beams. For direct drive targets, the beams would be configured symmetrically. With indirect drive, the beams would be divided into two clusters in order to fire into two tiny holes, one on each end of the target. For direct-drive targets absorption of intense one-micron wavelength laser light would be low (approximately 20 percent). In addition, Shiva's 20 laser beams could not achieve sufficiently uniform illumination for high quality direct-drive implosions. For indirect drive targets, most of the laser light would be trapped and absorbed in the hohlraum (unless plasma instabilities induced strong stimulated reflection). Hohlraum radiation processes would enhance implosion symmetry, and kilovolt energy thermal photons would ablate matter faster than electron volt laser photons. This faster ablation rate would further reduce growth rates of fluid instabilities.

Figure 13. Twenty beam, 10-kilojoule, 1micron wavelength Shiva laser

However, plasma instabilities enhanced by plasma trapped in the hohlraum might reflect a significant fraction of the laser light and generate enough hot electron preheat to prevent isentropic implosion of the DT fuel.

Lindl's calculations indicated that with short wavelength lasers high performance target concepts (including optimum pulse shaping, sustained subsonic ablation, isentropic compression, pusherless capsules, TN propagation, etc.) could be utilized in indirect-drive targets in spite of the effects of plasma instabilities (23). I was persuaded by Lindl's calculations. Emmett and I agreed that Shiva's and Nova's beams should be configured for indirect-drive targets.

Meanwhile KMSF scientists led by Brueckner generated neutrons in laser implosion experiments conducted in 1974 with DT-filled glass microballoons, and published a review of laser

fusion theory.(24) Our codes predicted correctly that KMSF's implosions were low-density exploding pusher, not high density.

<u>First Livermore Laser-driven Implosions</u>

Beginning in 1975, Livermore's second generation two-beam Janus laser directly imploded DT-filled, glass micro-balloon exploding pusher targets and generated fusion neutrons. Then, successively larger Cyclops and Argus one- and two-beam lasers imploded larger scale exploding pusher targets and achieved record neutron yields.

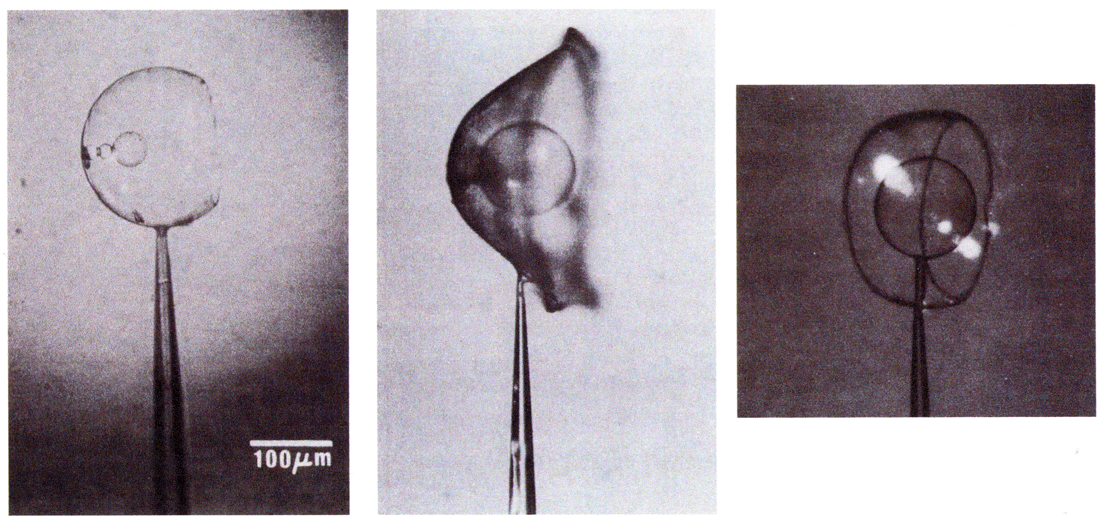

Figure 14. Examples of Exploding Pusher Targets used in 1970s experiments. Note 100 micron scale.

In 1976, we focused our lasers on indirect-drive targets which generated fusion neutrons with thermal radiation-heated exploding pusher capsules. Lindl led the target design effort. Shortly after our success, we were visited by Soviet scientist Lenid Rudakov who discussed an idea for a pulsed-power-driven, indirect-drive ICF target. Because of classification, we were not able to tell Rudakov that the indirect-drive approach to ICF had been calculated at Livermore since 1960 and that we had recently demonstrated successful experiments. Later, in the 1980-90 period, DOE declassified the indirect-drive approach.

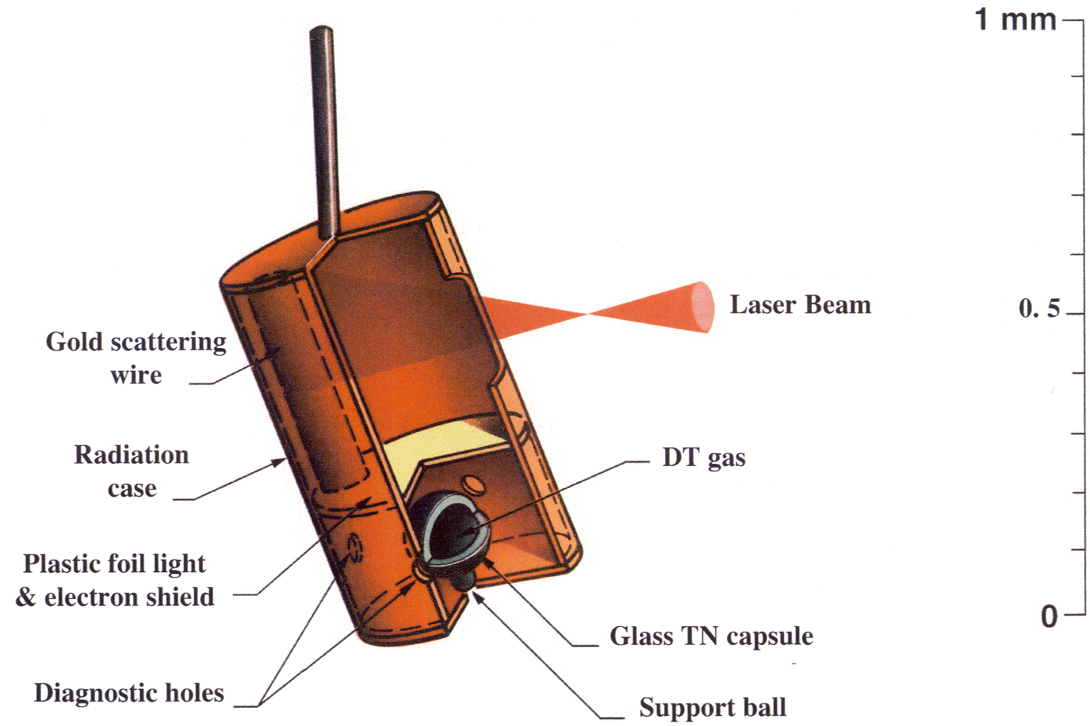

Figure 15. Model of the target used in the first successful indirect-drive laser driven experiment

100 Times Liquid Density Campaign

Implosion of DT to one hundred times liquid density was the principal objective of our Shiva experiments. X Division physicist, Bill Mead was lead target designer in this campaign.

We were surprised when disastrous numbers of super-thermal electrons were generated by intense laser light focused into the small hohlraum. "Hot" electrons penetrated and heated the fusion capsule, so that compression to high densities was not possible. Plasma instabilities also reflected light out of the hohlraum.

Fortunately, we had developed state-of-the-art capabilities to diagnose and understand what was happening and to rapidly fabricate improved target designs.

With advanced diagnostics, the Laser Experiments Program led by Hal Ahlstrom measured super-thermal X-rays generated by

hot electrons, and laser light reflected out of the entrance holes to the hohlraum. Kruer's plasma physics group generated theoretical estimates and supercomputer calculations of these plasma instabilities which were consistent with the experimental measurements. We increased the size of the hohlraums and changed the temporal pulse shape and laser focusing in the hohlraum to weaken the plasma instabilities and reduce preheat relative to the ablation pressures. Implosion to one hundred times liquid density was then achieved.

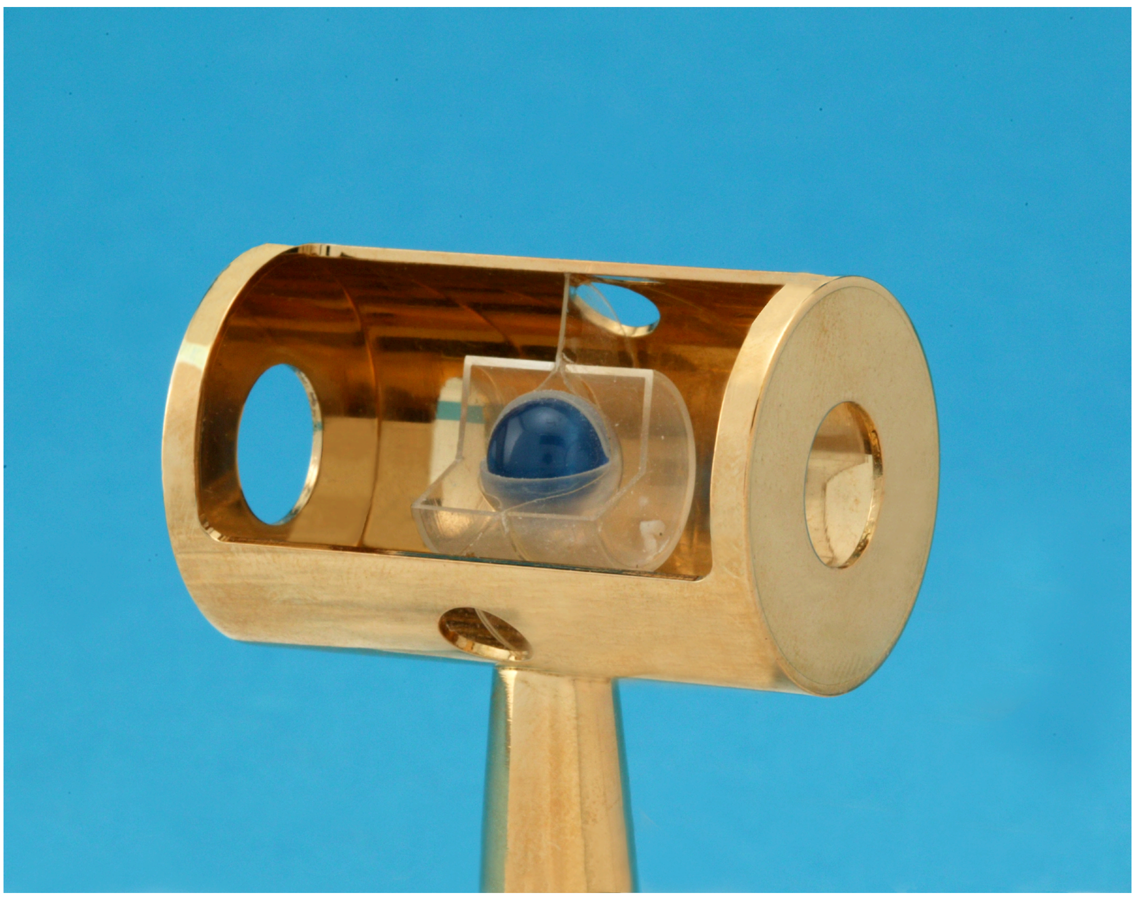

Figure 16. Model of target which imploded DT to 100 times liquid density in Shiva experiments. (Note scale of actual target was approximately a millimeter.)

Short Wavelength Capability Added to Nova—Foster Committee

Our target designers and plasma physicists concluded the 100 KJ Nova laser would need a short wavelength capability. But this capability had not been included in the plans and 200M$ cost estimate submitted to DOE and Congress. Substantial additional funds would be needed to convert Nova's 1.06 micron wavelength light to short wavelengths.

In the late seventies, TRW Vice-President John Foster (former Livermore director who initiated Livermore's first laser fusion program in 1962) chaired a DOE Experts Committee that reviewed the U. S. ICF program, including Nova plans. Col. Tom Johnson, a physics professor at West Point, and strong proponent of ICF served as Foster's principal staff assistant. At Foster's request, I served as a special advisor to the Committee and participated in the Committee's technical discussions.

After intense discussions, the Foster Committee recommended that half of the 20 beams planned for Nova should be eliminated to provide funds for a short wavelength capability on the remaining ten beams (25). With only ten beams, a 50% wavelength conversion efficiency, and a reduced material damage threshold due to use of short wavelength light, Nova's output would be reduced to 30 kilojoules of one-third micron laser light.

Ignition did not seem possible with hundred kilojoule class lasers—until the fast ignitor and high performance target breakthroughs in the nineties.

Foster's committee also recommended that ICF's major goal be upgraded to ignition of propagating burn. A megajoule-scale driver would probably be required! Foster recommended to DOE and to Congressional leaders that ICF continue to receive strong funding in spite of the plasma physics setback and the high cost of the MJ laser required for ignition.

Regarding ICF's energy applications, the committee found "no insurmountable roadblock to the practical achievement of electrical power generated by ICF." The principal recommendations were:

- Define the minimum (driver) energy for propagating burn

- Develop high-efficiency, low-cost drivers
- Understand beam target coupling
- Demonstrate commercial target fabrication technology
- Define practical reactor concepts

The committee noted, *"One of the chief advantages of ICF is that the driver is separate from the reactor vessel itself, and can be removed some distance. Consequently, an ICF reactor can have a relatively small containment volume, and its components are not subjected to neutron bombardment and activation."* (25)

<u>Halite/Centurion and Heavy Ion Accelerators</u>

I led Livermore's efforts in the 1970s to initiate the Halite and Heavy Ion Fusion programs. The Halite underground nuclear test program explored the implosion of smaller and smaller capsules of DT to establish the feasibility of ICF and if possible, determine the required driver energy for ignition. The HIF program initiated development of high rep rate, high efficiency, multi-megajoule accelerator drivers for use in ICF power plants. "X" Division physicist Hank Shay led the Halite program. Livermore's HIF target efforts were led by X Division physicist Roger Bangerter. The HIF accelerator development program was centered at the Lawrence Berkeley Laboratory.

Los Alamos conducted a Centurion program in parallel with Livermore's Halite program. Detailed results of these two multi-year programs remain classified, as are results of a similar Soviet program. Obviously, the U. S. would not be building a giant NIF to achieve ignition if this goal were inconsistent with results of H/C nuclear experiments. The results of these experiments greatly increased confidence in the ICF program.

To support the HIF program, we developed a heavy ion energized indirect drive target design. We defined specifications for the accelerator including energy, pulse shape, focusing and heavy ion energy and charge state requirements. ICF reactor parameters were provided, including the distance and plasma density through which the converging heavy ion beam must focus, and effects of small fusion explosions on the beam output mechanism.

Heavy ion accelerators may provide practical drivers for future multi-gigawatt ICF power plants. They are highly efficient (possibly 25%), the repetition rate can be high enough to drive several reactors (possibly 10 Hz or more), and the beam can be rapidly switched and transported through vacuum pipes to several one-GW reactors located in a reactor farm. This time sharing feature reduces the driver cost per reactor because the accelerator cost increases much less than linearly with increasing repetition rate. A "reactor farm" where, for example, a single 3MJ accelerator supports 10 one-GWe fusion reactors may be an economically attractive option for geographical areas with a sufficiently high population density and energy demand.

Maxwell Prize—An opportunity

In 1981, the American Physical Society (APS) awarded the James Clerk Maxwell Prize for my "contributions to the genesis and progress of inertial confinement fusion . . ." As with the 1969 Lawrence Award, this prize provided enhanced political and scientific influence which I used to advance the ICF program.

In my Maxwell Prize Address to the Plasma Physics Division of the APS, I recommended that fusion energy development be accelerated because of the increasing risk of CO_2 induced global climate change and the national need to secure greater energy independence. I discussed progress in ICF with short wavelength lasers, including increased absorption and reduced effects of plasma instabilities.

I highlighted the Foster Committee's recent findings and powerful recommendations on ICF energy applications. Finally, I focused on the great economic challenge to the commercial success of fusion energy. Unless there is a significant cost advantage, fusion reactors will not be developed by governments or purchased in large numbers by the private sector. (26)

Physics Today, which printed my Maxwell Prize address, featured a color diagram of an ICF reactor scheme developed at Livermore which uses continuously renewable liquid lithium jets to absorb heat and nuclear radiation. This scheme is compact, comparable in size to a fission reactor.

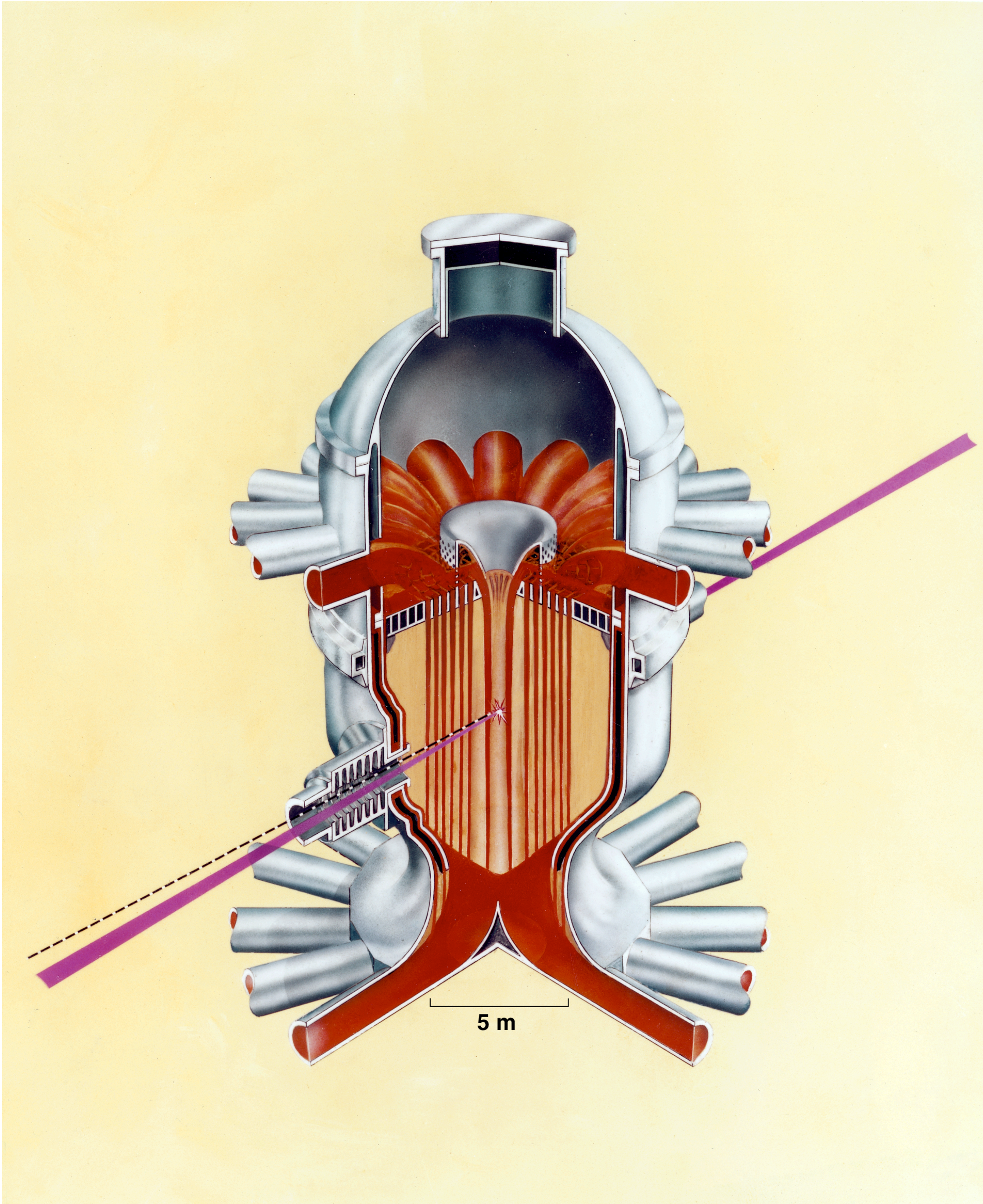

Figure 17. ICF reactor with liquid lithium walls; five meter scale corresponds to a 1000 megawatt reactor

Teller's Perspective—Late 1970's/Early 1980's

Teller predicted, "ICF would solve the third global energy crisis" after fission and MFE solved the first two. Teller also suggested that high power lasers would enable exploration of the physics of high energy and matter densities. He strongly supported Livermore's ICF program in Congress and encouraged our efforts at Livermore.

In the late seventies, Teller presented an honorary "Doctor of Thermonuclear Arts, Sciences, and Politics" degree: "DOCTORIS ARTIUM, SCIENTIARUM, RERUMQUE, PUBLICARUM IGNIS THERMONUCLEARII." Edward was also instrumental in my receiving an honorary Doctor of Science degree from the Florida Institute of Technology. I should have recognized that my ICF focused career would change.[6]

In 1983, after President Reagan's Strategic Defense Initiative was launched, Director Batzel promoted me to Associate Director for Physics, leader of Livermore's 400 person Physics Department. At my request, Batzel transferred X Division to the Physics Department.

I appointed John Lindl X Division Leader. Lindl focused on developing indirect-drive targets. Fundamental fluid and plasma instability problems were addressed leading to a sufficiently stable ignition target design for NIF. Bob McCrory at the University of Rochester developed direct-drive ignition target designs, including laser and optical innovations to address implosion stability and symmetry problems (27).

Emmett continued his strong leadership of Livermore's laser fusion program including development of approaches to high average power solid-state lasers suitable for ICF power plants (28).

NOVA Experiments/Batzel retires/Path Forward?

In the early eighties, pre-Nova experiments were conducted with the Novette laser, using two Nova technology beams.

[6] Past and present directors of Los Alamos and Livermore all had Ph.D.s. In the 1960s, Teller suggested I become his doctoral student—but this was not possible because of urgent Cold War priorities.

Figure 18. Nova ten-beam, 30 kilojoule, 1/3 micron wavelength laser

Nova became fully operational in the mid-eighties. An experimental program was launched to diagnose and understand the physics of laser energized hohlraums and radiation implosions. The principal goal was to develop a reliable estimate of the required size of an ignition laser. A "Precision Nova" upgrade program led by Mike Campbell enabled sufficiently detailed target experiments. This program also served to build strong support in the scientific community.

A "Technical Contract" approach was developed. Planning of experiments, theory, and calculations were coordinated with several national level advisory committees appointed by DOE, the National Academy of Science, etc. Campbell, Lindl, Erik Storm (a leader in Emmett's Laser Fusion Program) and others planned and executed this outstanding multi-year effort, which extended into the mid-1990s.

Lindl and Campbell received E. O. Lawrence Awards in 1994 for their outstanding contributions.

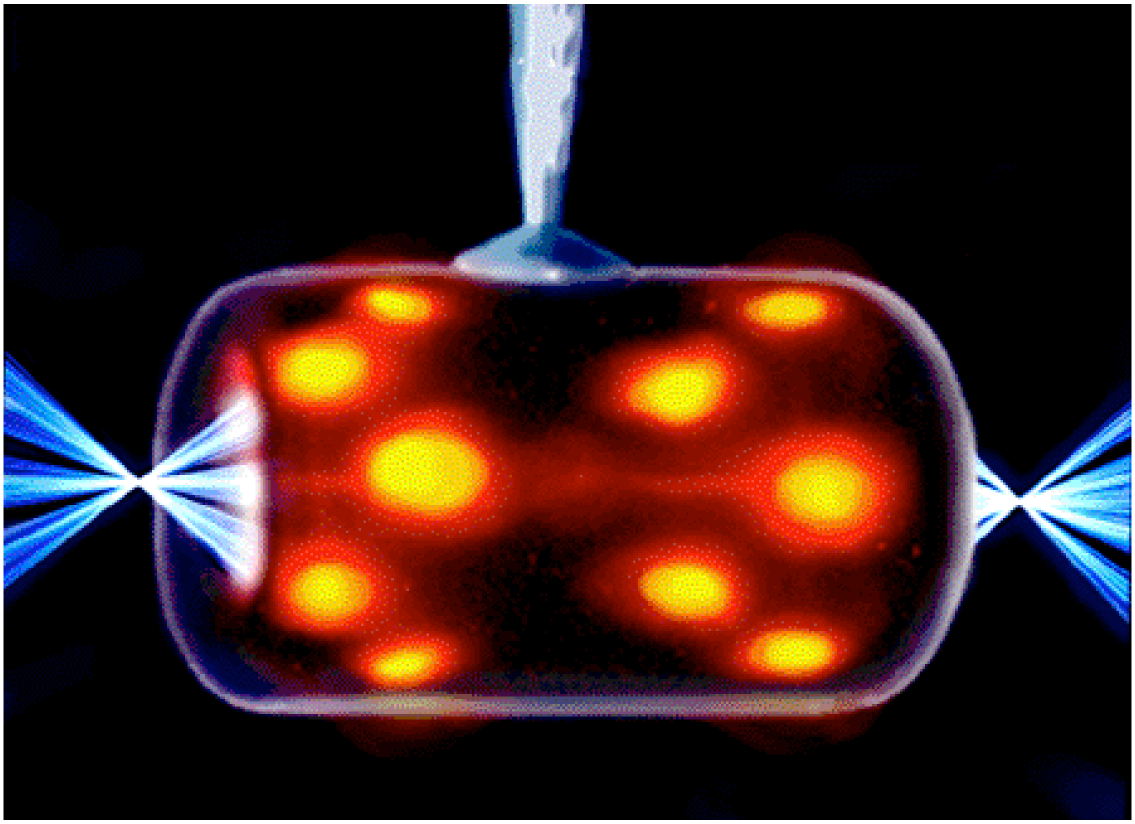

Figure 19. Nova indirect-drive target experiment: ten hot spots are generated by focusing of ten Nova laser beams inside the tiny gold hohlraum (scale several mm)

In 1987, Roger Batzel announced his plans to retire. During his 17 years as Livermore director, Batzel presided over the growth of a great laboratory with enormous potential and capability. He initiated Livermore's second generation ICF program and strongly supported ICF efforts. Batzel's successor would face apparently impossible problems in the fusion area. In 1987, Livermore's giant new 400M$ magnetic mirror machine was shut down so that U. S. MFE funding could be focused on Tokamak development. In the ICF area, multi-megajoule-scale ignition lasers could cost billions of dollars. The entire laboratory had a one-billion-dollar annual budget. For the weapons program, a billion dollars spent on nuclear tests would be more valuable. For future inertial fusion energy applications, these lasers would be too expensive.

In a nationwide competition, eighty candidates for Livermore director were nominated to succeed Batzel. I was one of them. I proposed a revitalization of LLNL, including acquisition of vastly more powerful computers and development of a large laser to achieve ignition.

Third Generation ICF Program, 1993 – 2005
National Ignition Facility and Fast Ignition Lasers/Targets

In early 1988, The University of California appointed me to a five-year term as Director of the Laboratory, with more than 10,000 employees and programs funded at a billion dollars annually. Livermore had leading roles in two national security areas, Nuclear Weapons and the Strategic Defense Initiative (SDI).

In the nuclear weapons area, I launched initiatives to insure nuclear weapons safety and to develop improved diagnostics of nuclear tests.

In SDI, major breakthroughs had been achieved by Wood, Teller, and Greg Canavan at Los Alamos. In July, I accompanied Teller and Wood, who briefed the SDI Brilliant Pebbles space-based ballistic missile interceptor system to President Reagan, Vice President Bush, and other top government officials. The president was delighted with a non-nuclear solution to the ballistic missile defense problem.

I launched long range campaigns to build a "21st century laboratory" prepared to address great challenges of the future. We proposed to develop large-scale laser isotope separation facilities, became a partner with Los Alamos and UC Berkeley in the Human Genome program, created technology transfer partnerships with private sector companies, and launched environmental, energy and science education programs.

My long-range ICF strategy was to develop an affordable megajoule-scale laser and ignite TN propagation for weapons and energy applications. As director of Livermore, I became deeply involved in the political aspects of ICF.

In the late eighties, we estimated that a ten megajoule laser would be required to achieve ignition and that such a laser could cost billions of dollars. The value to the weapons program was not high enough to justify this cost. We pursued efforts to achieve major cost reductions.

At the same time, we developed stronger relationships with Congress and strong partnerships with Sandia and Los Alamos, and the University of Rochester ICF program.

After twenty years of outstanding leadership, John Emmett retired. I appointed Emmett's deputy, Jim Davis to lead the Laser Fusion Program.

Weapons Budget Collapses

As the Cold War receded in the early nineties, Livermore's nuclear weapons and SDI budgets declined rapidly. Key Congresspersons asked, "Is a Livermore nuclear weapons laboratory needed in the post-Cold War world?"

In early 1990, President Bush visited Livermore and thanked the Laboratory and Teller, in particular, for outstanding contributions to national security throughout the long Cold War. Brilliant Pebbles was a center of attention. The president expressed strong confidence in Livermore's future.

In 1991, Edward Teller presented the first Teller Medals to Professors Nikolai Basov, Chiyoe Yamanaka and Heinrich Hora and to me.[7] In acceptance remarks, I recalled Teller's role as father of ICF. Subsequently, many Livermore scientists have been awarded Teller Medals: John Lindl, George Zimmerman, Mordy Rosen, Steve Haan, Larry Suter, and Max Tabak, and Michael Campbell and Joe Kilkenny (both now employed by General Atomics).

Breakthroughs

In 1992, breakthroughs in ICF emerged. Improved understanding of plasma and fluid instabilities and confidence in

[7] Professors Heinrich Hora and George Miley proposed the Teller Medal awards and founded a series of ICF meetings, "Laser Interactions and Related Plasma Phenomena."

calculations were achieved in highly diagnosed experiments. Target design calculations used more powerful codes and supercomputers. Advanced targets were developed that ignited in calculations with a 1-2 MJ laser. (29,30)

In parallel with major advances in targets, Laser Program experts identified a series of technological breakthroughs that could reduce the cost of a 1-2 MJ laser to a billion dollars. These advances included a large aperture optical switch, which made possible giant multi-pass laser amplifiers, breakthroughs in large-scale manufacturing of laser glass, processes for rapidly growing giant KDP crystals and increases in the damage threshold of optical components. (31)

Campbell led a program to construct Beamlet, a prototype of an advanced multi-pass laser architecture, and a research plan was formulated. Subsequently, this facility demonstrated many of the new technologies required for NIF.

Political breakthroughs also emerged in Congress and in our alliances with other laboratories.

For a May 1992 visit to Livermore by Secretary of Energy Watkins, I decided to present two major proposals that defined my strategic vision for the Livermore Laboratory in the 21st century. The first proposal was for a National Ignition Facility (NIF). Watkins' reaction was strongly negative. All available funds were needed to support the shrinking DOE weapons complex. He criticized me personally for the NIF proposal, "You should be ashamed!" I asked Watkins to chair the DOE decision process on NIF and he agreed.

Watkins strongly supported our second major proposal for a greatly expanded program to address the growing threat of nuclear terrorism and to strengthen nuclear arms control efforts. After Watkins returned to Washington, the White House and DOE proposed a several hundred million dollar national initiative. Watkins invited me and the directors of Los Alamos and Sandia to support this initiative in Congress. In summer '92, I announced a Non-proliferation/Arms Control/International Security program at Livermore. Building on Livermore strengths in this area, this program has grown rapidly.

Later in 1992, a powerful geopolitical catalyst emerged, when Congress voted to suspend nuclear testing. In November, Bill Clinton, an opponent of nuclear testing, was elected president.

I recognized that major new experimental and computational facilities would be required to maintain high confidence in the reliability of the nuclear stockpile without nuclear testing. NIF would enable nuclear effects experiments, and could be used to address weapons physics issues and train future generations of nuclear weapons experts. I anticipated strong presidential support of NIF, since our British and French nuclear allies would also need large lasers to support their nuclear stockpiles.

Shortly after Clinton's election, I drafted a three-laboratory letter to Secretary Watkins requesting his approval of NIF to support the weapons program in an era of no nuclear testing. Los Alamos Director Sig Hecker and Sandia President Al Narath helped prepare and signed this January 6, 1993 letter. *". . . the proposed NIF is a multi-laboratory inertial fusion facility whose goal is to achieve ignition and propagate thermonuclear burn in ICF targets.*" We emphasized the DOE ICF Advisory Committee's strong support of the technical basis for support of NIF, and that of the NSF Committee and key elements of the scientific community (thanks to the outstanding many year-long efforts of Lindl, Campbell, McCrory, and Marshall Schluyter, leader of DOE's ICF Program).

I was deeply concerned because Secretary Watkins had not agreed that the value of NIF to the weapons program justified the high cost. On January 15, five days before leaving office, Watkins authorized "Key Decision Zero," which established a Mission Need for the National Ignition Facility and funded the Conceptual Design process. (Laser, I learned that Watkins had refused to approve this KDO until a leading staff member stood on Watkins desk and argued passionately for NIF).

<u>NIF Launched — Third Generation ICF Program</u>

At an early 1993 Livermore ceremony, I announced the first steps to build the giant megajoule-scale National Ignition Facility.

"Thirty years ago, the Livermore Laboratory initiated the world's first laser fusion program. The far-reaching goal was to achieve ignition of small fusion explosions in the laboratory, both for weapons physics applications, and to harness fusion for civil power. Throughout these 30 years, LLNL has led the world in inertial fusion"—

- *"inventing both direct and indirect drive targets*
- *"building a series of ever-larger ultra-high power solid state lasers extending from a one-joule scale to the 100,000 joule-scale Nova"*
- *"conducting underground experiments, which bounded the ICF ignition requirement"*
- *"conducting a series of highly diagnosed laser implosion experiments which have provided a solid scientific foundation for ICF."*

"In the past five years, the Laser Program has made extraordinary advances in targets, laser, and experiments."

"Today, the U. S. ICF program is poised to take the step to ignition."

"The national needs that ICF addresses have become time urgent with the passage of the Hatfield Amendment limiting nuclear testing."

"The ICF program in general and this Livermore Laboratory in particular are challenged again to achieve a new generation of extraordinary advances in science, technology, and program management."

My decision to launch NIF was one of the most difficult and important decisions in the Laboratory's history. Launching a billion dollar program (exceeding the lab's annual budget) to build a revolutionary laser that depended on several breakthroughs was a daring high-risk decision. I gave great weight to the potential payoffs for national security, energy, and for the laboratory. I anticipated that meeting the NIF construction and ignition "stretch goals" would help create and define a great 21st century national laboratory.

In spring 1993 at Los Alamos, President Clinton met with LANL Director Hecker, SNL President Narath, and me to discuss

our weapons laboratories' initiatives in the post-Cold War world. Clinton was strongly supportive and enthusiastic. In a memorable speech, the President thanked our three laboratories declaring *…when we needed to win the Cold War, to contain and then triumph over Communism, the ideas that made it possible came out of these laboratories."* On the flight back to Livermore, I thought about NIF and the great potential of these laboratories in the 21st century—including harnessing fusion energy, and the defense of free and open societies against the growing threat of terrorists armed with nuclear and other weapons of mass destruction.

Stockpile Stewardship Program

In 1993, Clinton's national security staff began to develop a "science based stockpile stewardship" strategy, with NIF as a centerpiece. Vic Reis, head of DOE's Defense Programs, had a leading role in developing this strategy.

When Jim Davis retired in fall '93, I appointed Michael Campbell to lead our ICF Program. Campbell had outstanding leadership abilities. He initiated and led a collaborative national ICF program, and led efforts to achieve the innovations required for NIF's success.

Revolutionary Advance: Fast Ignition

Campbell and Mike Perry initiated development of a large-scale, "fast-ignitor" laser — a high energy, ultra intense chirped pulse laser. X-Division physicist Max Tabak developed very high-gain, fast-ignited target designs, and proposed a revolutionary new fast ignitor approach to ICF (32) where a multi-beam compression laser is used to compress the DT to one thousand times liquid density and a separate petawatt/10 picosecond laser beam is used to ignite the compressed DT. With a megajoule energy compression laser, gains of 300 could be achieved with Tabak's targets because the implosion velocity required to achieve isobaric central spark ignition is much higher than the velocity required to isentropically compress the DT to densities required for efficient TN burn.

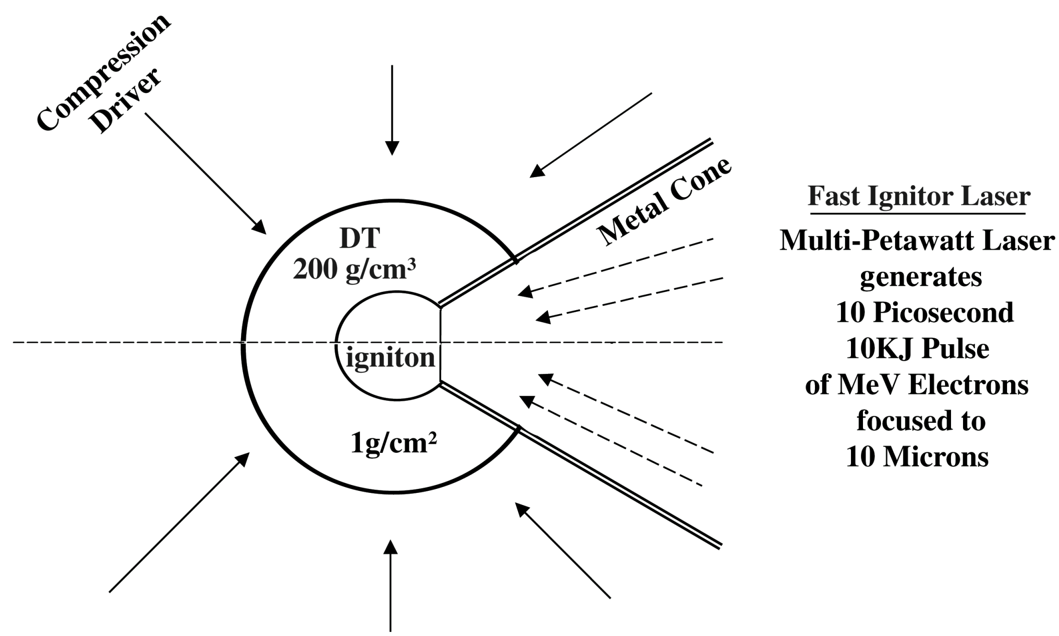

Figure 20. Tabak Fast Ignitor target

Political Challenges

My five-year term as Livermore director had a turbulent ending. High-level congressional, DOE and University of California officials continued to question the future of Livermore. However, I strongly supported the position that with no nuclear testing, two weapons design labs were needed to provide peer review and ensure confidence in the nuclear stockpile.[8] I also supported additional nuclear test experiments to develop technologies for rapidly disabling booby-trapped terrorist nuclear weapons at a distance. I requested that my term as director be extended. This request was denied.

When I stepped down in May 1994, there was a controversy over my highly publicized farewell warning to congressional national security committees that the post-Cold War decline in the

[8] DOE appointed a national Galvin Commission to evaluate the missions of Livermore and other DOE Labs. Later after extended discussions, President Clinton decided that Livermore would continue as a weapons lab.

nuclear weapons budget was excessive, and that the United States was not adequately preparing for the growing threat of nuclear terrorism.

An advisor to President Clinton responded to this controversy by requesting a meeting and asking for my recommendations. I recommended presidential support for NIF to sustain nuclear weapons expertise and capabilities in a future with an increasing risk of nuclear terrorism and uncertain long-term geopolitical risks, and to develop fusion energy in the 21st century.

My successor as Livermore director, C. Bruce Tarter, provided strong leadership for the Laboratory, including support for NIF. Vic Reis' efforts in the U. S. government on behalf of NIF were invaluable. After final DOE approval in 1997, construction of NIF was initiated. On a sunny afternoon at the groundbreaking ceremony, the near impossible path to NIF's launching was forgotten. We looked forward to great challenges and opportunities.

Potential Disaster — Recovery

After several years, challenges in the NIF construction project led to cost growth that placed the project in jeopardy. In 1999, a crisis erupted when we learned that NIF costs would far exceed the approved funding level. The Secretary of Energy and key members of Congress strongly objected. Campbell stepped down. Director Tarter appointed weapons program Associate Director George Miller to lead the NIF program. Ed Moses from the laser program became Miller's deputy. They provided strong leadership.

After intense reviews by high-level government and U. C. panels, revised NIF plans were developed. Total costs increased to more than three billion dollars, completion was delayed several years, and ignition was rescheduled for 2010. The long delay of NIF's completion has increased risks of divisive politics and budget shocks.

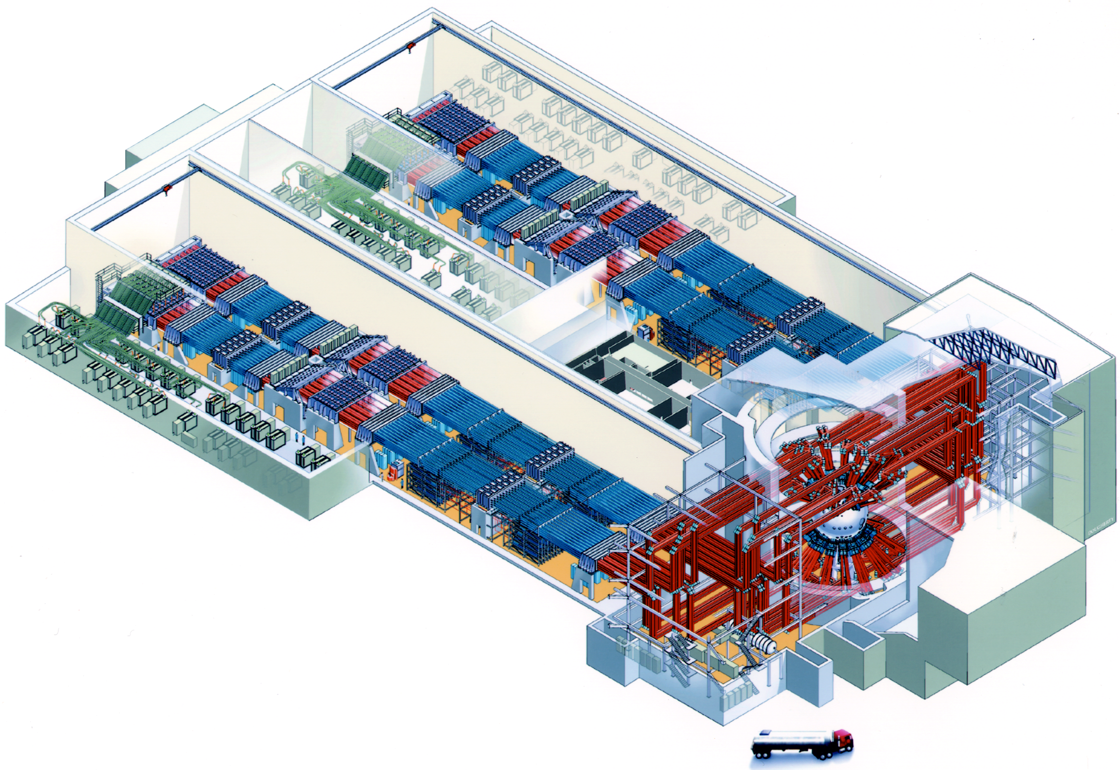

Figure 21. Cutaway drawing of the NIF laser and target chamber area (Note truck which indicates scale of NIF)

In 2002, nuclear weapons program leader Mike Anastasio succeeded Tarter as director of Livermore. Anastasio has strongly supported NIF and ICF. It is remarkable that six consecutive Livermore directors have supported Livermore's leading role in ICF over a period of more than forty years.

Path to Fusion Energy—Advanced Targets

At the 2002 fiftieth anniversary celebration of Livermore's founding and at the International Conference on Emerging Nuclear Energy Systems meeting in Albuquerque, I explained how advanced targets could achieve gain 1000 with a few hundred kilojoules of laser energy (33). TN burn is propagated from a minimum mass of high density, fast-ignited DT into a much larger mass of far lower

density efficiently compressed DT. Maximum gains result when most of the DT is efficiently compressed, possibly in a non-ablative implosion with a dense high Z pusher, possibly using laser ignited exothermal propellant.

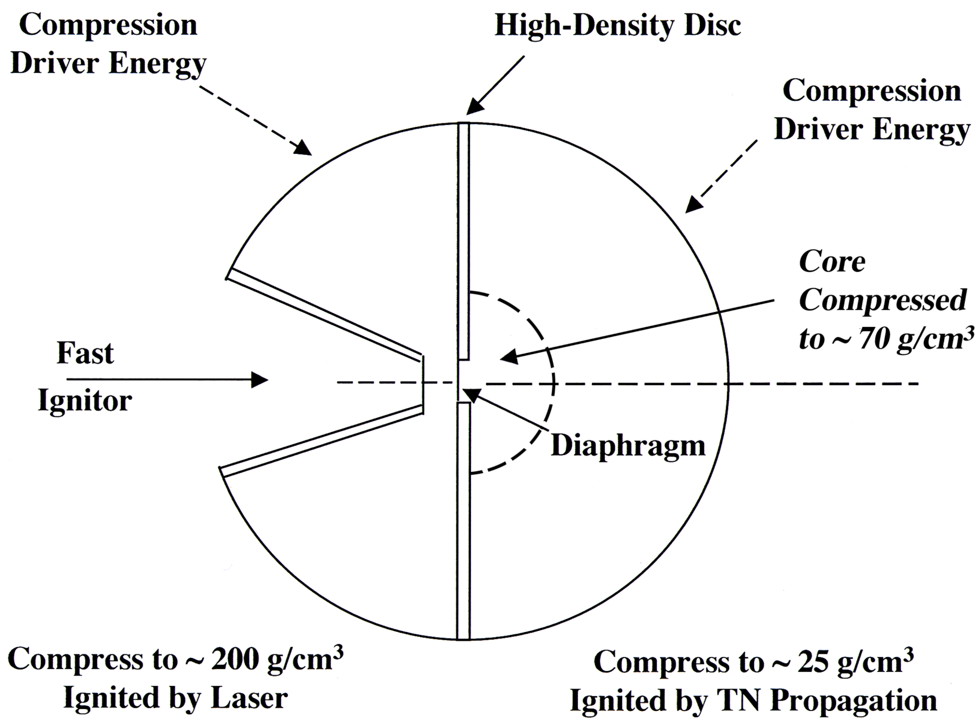

Figure 22. "Hemispheres" example of high performance target

TN burn may be propagated through a region of intermediate densities (a density gradient or a stepwise density distribution with roughly a factor of three reduction in density for each $1g/cm^2$). The density and implosion efficiency of the yield-producing region are optimized to minimize the compression laser energy and increase the fusion yield, while at the same time, the density of the ignition region is optimized to minimize the ignition laser energy.

Dense pushers may increase target performance. A pusher in the ignition region reduces the minimum DT mass and the required fast-ignitor laser energy. A pusher in the high-yield region reduces the required density, enabling high efficiency non-ablative

implosions, and possibly implosions driven by laser ignited exothermal propellant.

Future: Ignition and Energy

Walking through the awesome National Ignition Facility recently, I recalled words from H. G. Wells' prophecies. Here "student teachers of the universe" will unleash "the secret power of the atom" and discover "knowledge as yet beyond knowing."

One hundred ninety-two giant laser beams will simultaneously focus a combined 500 terawatt pulse of blue laser light into a tiny target designed with the world's most powerful supercomputers. In nanoseconds less than a milligram of DT fusion fuel will be imploded to densities and temperatures higher than those in the center of the sun—igniting a fusion microexplosion, and propagating thermonuclear burn.

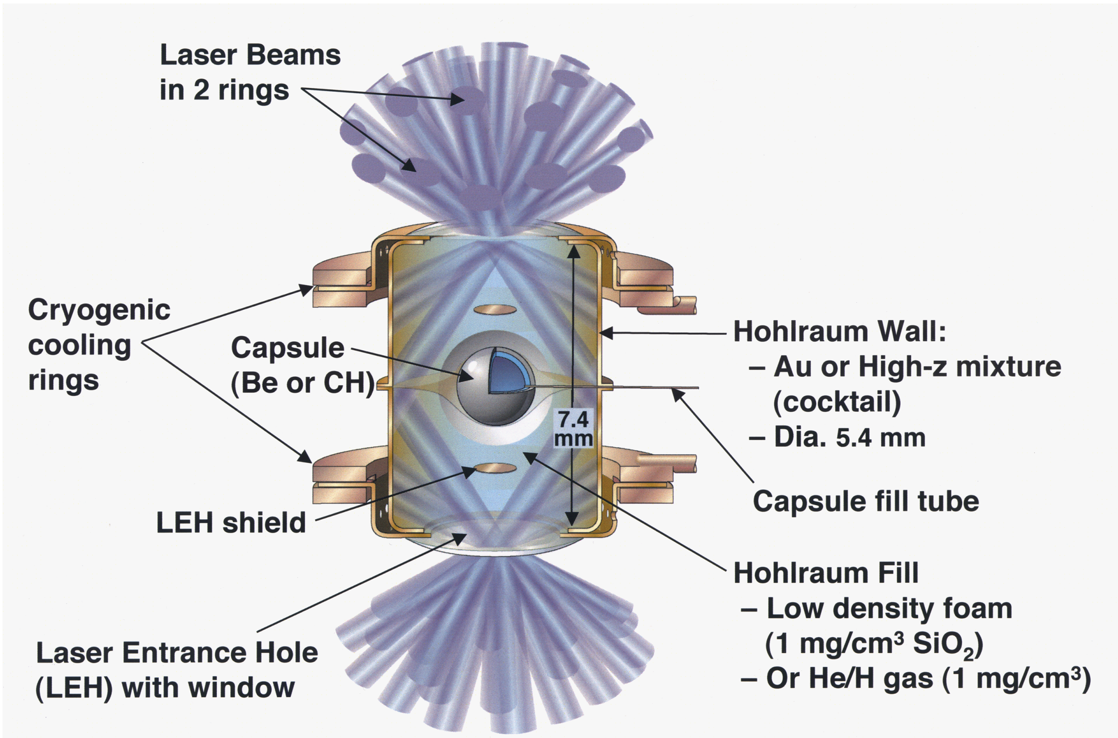

Figure 23. 2005 Ignition Target Design for NIF

Like the Manhattan A-bomb Project and the Apollo Lunar Program, the ignition of fusion with lasers is a large-scale endeavor with revolutionary potential and risks.

As with the parallel gun and implosion approaches in the Manhattan Project, risks in the NIF ignition campaign could be reduced by use of two fundamentally different target designs. Direct drive targets require almost the same record high implosion velocities and convergence ratios used in NIF's indirect drive targets. Direct drive targets ignited by a final shock may have a larger energy margin. However, stability, preheat, and mix margins may be smaller.

If results of coupling experiments with petawatt laser beams are favorable, fast ignition targets may provide a promising option for risk reduction. This approach would greatly reduce the

required laser energy and reduce by more than two-fold the implosion convergence and velocity requirements.

Up to one hundred kilojoules of ten picosecond laser energy may be required for fast ignition. Then, up to 20-30 NIF beams would require augmentation. However, much smaller energies would suffice for ignition if experiments show the target coupling efficiency can be sufficiently enhanced by innovations in target design, including use of a focusing cone, pusher, a hollow central cavity, and intense laser-generated magnetic fields.

In any event, augmentation of NIF will be required to provide a fast ignition capability so that high gain targets can be developed for both stockpile stewardship and energy applications.

Energy

Systems' studies predict that ICF power plants using large lasers would be economically competitive with other energy sources. With small low cost lasers, ICF energy systems can have a significant cost advantage over alternative energy systems that have much higher fuel costs or capital costs. Reducing the laser size and cost of ICF power plants would create an economic incentive for government funding of a demonstration reactor development program and for private sector funding of the construction of ICF power plants.

Thermonuclear propagation in high- performance targets can reduce laser size and cost by coupling two regions with radically different densities and implosion efficiencies.

ICF's Long-Range Energy Potential

Advanced energy systems are likely to emerge in the future. A few days before 95-year-old Edward Teller died in September 2003, he discussed the possibilities of novel fission and fusion schemes with Lowell and me. Teller emphasized the future is uncertain and scientists and engineers should cooperate globally to shape the future.

In a Darwinian competition of future energy systems, ICF may have a "genetically" enhanced rate of improvement. Driver,

target, and reaction chamber systems are physically separated and largely decoupled. This separation and decoupling enables a high potential for innovation. The rate of target innovation will be accelerated by the development and use of increasingly powerful supercomputers and design codes, and data from highly diagnosed experiments conducted with NIF and other facilities. Commercial and national security applications will continue to drive a high rate of innovation in lasers. The materials revolution will enable innovation in targets, lasers and optics, reaction chambers, and thermal-electric generating efficiency.

ICF has a remarkable long-range potential for improvement. The overall efficiency of current ICF reactor designs is roughly 10^{-3}, comparable to that of early steam engines. Higher efficiency drivers, implosions, TN burn, and thermal-electric conversion are possible. We have barely begun to harness fusion energy's million-fold advantage over chemical energy.

"The past is but the beginning of a beginning, and all that is or has been is but the twilight of the dawn." H. G. Wells, *The Discovery of the Future*.

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Acknowledgements

In this chapter, I have focused primarily on the ICF program at Livermore. Many other laboratories and researchers have made

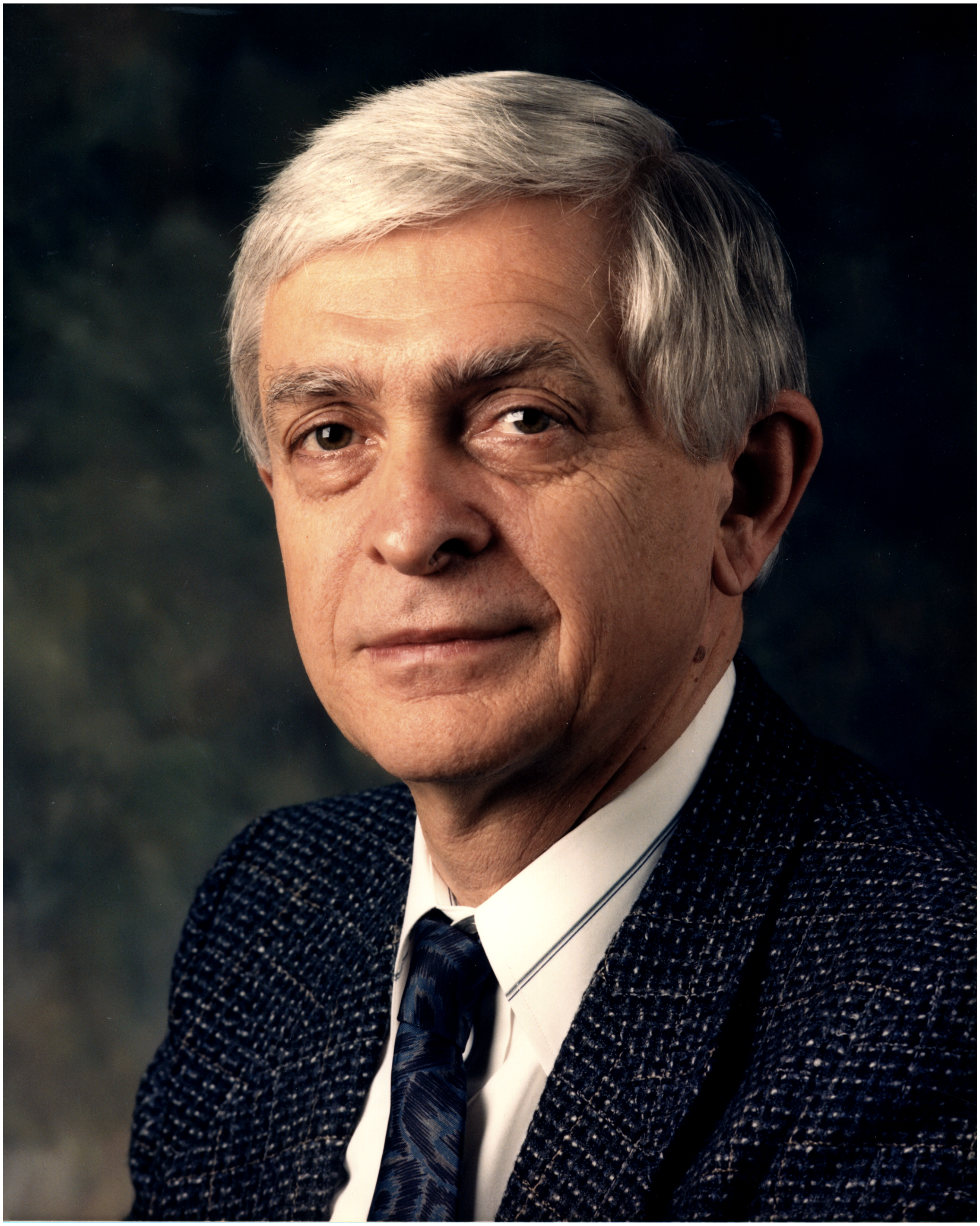
vitally important contributions, including Los Alamos National Laboratory, the University of Rochester Laser Lab, Naval Research Laboratory, KMS Fusion Laboratory, and Sandia National Laboratory in the United States, and laboratories and researchers in France, Russia, Japan, England, Germany, Spain, Israel, Italy, and Australia.

I would like to acknowledge the outstanding efforts of thousands of people in ICF programs – scientists, engineers, technicians, administrators, and managers and political leaders. Without their efforts, ICF's remarkable half century of progress would not have been possible, and ICF's future success *will* not be possible.

I strongly encourage the ongoing major efforts to achieve ignition. Outstanding achievements in the development of ignition targets are summarized in recent publications by John Lindl and colleagues (23,29,30). Several scientists have been awarded Teller Medals and have reported progress in a recent book, *Edward Teller Lectures* (34). Outstanding achievements are being made in the development of the giant U.S. and French ignition lasers. Unfortunately, no award comparable to the Teller Medal exits in the ICF laser area. (I strongly recommend establishment of such awards.)

I am pleased to acknowledge more than fifty years of key contributions to ICF by John Foster – beginning with his pure fusion group in 1954, his launching of the first laser fusion program in 1962, his contributions to the Livermore Laboratory's "can-do-the-impossible" spirit, his leadership of the DOE "Foster Committee" in the late 1970s, and his many years of strong support for ICF and the National Ignition Facility in the U.S. government.

Biography of John H. Nuckolls for Pioneers' Book



John Nuckolls is Director-Emeritus of the University of California Lawrence Livermore National Laboratory, where he served as director from 1988-1994 and has pursued ICF research and development for fifty years.

His fascination with inertial fusion began as a seventeen-year-old in 1948 when he read popular science articles on H-bombs and the fantastic potential of nuclear fusion: the energy source of the sun and stars could be created on earth; unlimited fusion energy could power civilizations for millions of years and propel spaceships to the stars. He studied his father's nuclear physics books and the Smyth Report on development of the A-bomb, and devised a primitive fusion explosive scheme.

In 1952, when Los Alamos detonated the first thermonuclear explosion, he was a physics student at Wheaton College near Chicago, and read about Edward Teller, "father of the H-bomb"—and the new Livermore Laboratory. The Cold War escalated while he was a physics graduate student at Columbia University studying quantum mechanics and relativity, atomic and nuclear physics, etc.

In 1955, he responded to a recruiting ad in the Columbia newspaper and was employed by the University of California Radiation Laboratory's Thermonuclear Explosive Design Division at Livermore.

His contributions to the design of high efficiency thermonuclear devices, including clean explosives, were recognized in 1969 when President Nixon and the U. S. Atomic Energy Commission granted himan Ernest Orlando Lawrence Memorial Award.

In the seventies and early eighties, he focused on inventing ICF targets, initiating the declassification of ICF, and developing major ICF programs. These efforts were recognized in 1981 with the award to him of an American Physical Society James Clerk Maxwell Prize for "outstanding contribution to the genesis and progress of inertial confinement fusion" and "insights into fundamental physics issues which served to guide and inspire the technical evolution of the field".

In the late seventies, Edward Teller presented an honorary degree "Doctor of Thermonuclear Art, Science, and Politics" and the Florida Institute of Technology awarded an honorary Doctor of Science degree.

A few months after the U. S. Strategic Defense Initiative was launched in 1983, Nuckolls was appointed Associate Director for Physics. In 1988 as the Cold War was coming to an end, he was appointed Director of the Livermore Laboratory by the University of California, and served until 1994. His contributions to ICF were recognized by an Edward Teller Medal in 1991. When nuclear testing ended in 1992, Nuckolls requested DOE approval of the National Ignition Facility, and strongly accelerated a program to address nuclear proliferation, terrorism, and other weapons of mass destruction in the 21st century.

In the nineties, Nuckolls served the U. S. Department of Defense, the U. S. Strategic Command, and the Director of Central Intelligence as a member of high level advisory committees.

Nuckolls' contributions have been recognized by awards from the Secretary of Energy and Secretary of Defense, and by election to the National Academy of Engineering, and Fellowships in the American Physical Society and the American Association for Advancement of Science.

In 2002, Nuckolls published a new approach to very high performance targets designed to reduce the size and cost of fusion lasers sufficiently to enable economically attractive ICF power plants.

(Reprinted from Nature, Vol. 239, No. 5368, pp. 139–142, September 15, 1972)

Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications

JOHN NUCKOLLS, LOWELL WOOD, ALBERT THIESSEN & GEORGE ZIMMERMAN

University of California Lawrence Livermore Laboratory

Hydrogen may be compressed to more than 10,000 times liquid density by an implosion system energized by a high energy laser. This scheme makes possible efficient thermonuclear burn of small pellets of heavy hydrogen isotopes, and makes feasible fusion power reactors using practical lasers.

THERMONUCLEAR burning occurs extraterrestrially in stars and terrestrially in nuclear explosions[1]. The specific thermonuclear burn rate is proportional to density

$$\varphi \sim \rho \, \overline{\sigma v}$$

where φ is the fractional burnup, ρ is the density, and $\overline{\sigma v}$ is the Maxwell velocity-averaged reaction cross-section. Consequently, except at high fuel depletions, the thermonuclear energy production at a fixed ion temperature is proportional to the Lawson number, a product of density and confinement time[2]. In conventional controlled thermonuclear reactor (CTR) approaches, the density is limited by material properties, and the objective is to achieve sufficiently long confinement times by the use of electromagnetic fields[3]. In the laser-fusion approach to CTR, the objective is to achieve sufficiently high fuel densities, while the confinement time is determined by the inertia of matter. Spherical compression of 10^4-fold via the laser implosion scheme described here reduces the laser energy required for CTR by more than one thousand-fold, from more than 10^8–10^9 J—which is so large as to be currently impractical—to $\sim 10^5$–10^6 J, assuming laser and thermal/electric efficiencies of 10% and 40% respectively[4]. One kJ of laser energy may be sufficient to generate an equal thermonuclear energy.

Compression

Hydrogen in the centre of the Sun is believed to exist at more than one thousand times liquid density, and at pressures greater

The electrons in white dwarf cores are Fermi-degenerate, so the pressure is a minimum determined by the quantum mechanical uncertainty and exclusion principles[7]. The pressure of dense hydrogen with Fermi-degenerate electrons is[8]

$$P = \frac{2}{3} n_e \varepsilon_F \left[\frac{3}{5} + \frac{\pi^2}{4}\left(\frac{kT}{\varepsilon_F}\right)^2 - \frac{3\pi^4}{80}\left(\frac{kT}{\varepsilon_F}\right)^4 + \cdots \right]$$

where n_e is the electron density; $\varepsilon_F = \frac{h^2}{8m}\left(\frac{3}{\pi} n_e\right)^{2/3}$ is the Fermi energy; kT is the thermal energy; h is Planck's constant, and m is the electron mass. At 10^4 times liquid density ($n_e = 5 \times 10^{26}$), the minimum hydrogen pressure occurs when $kT \ll \varepsilon_F$, and is $\sim 10^{12}$ atmospheres.

Pressure: Implosion, Ablation

To compress hydrogen on Earth to these stellar densities, the required pressures must be generated by means other than gravitational. The pressures generated mechanically or chemically are generally limited to $\lesssim 10^6$ atmospheres by the strengths of chemical bonds. However, chemical explosive pressures have been multiplied from less than 10^6 to more than 10^7 atmospheres by implosion. The pressure applied to an implosion system does PdV work generating kinetic energy which is converted near isentropically to internal energy concentrated in the compressed volume. Because pressure is energy per unit volume, the maximum average pressure equals the applied pressure multiplied by the compression ratio. Additional pressure multiplication occurs near the centre because of convergence effects[9]. The pressure multiplication factor may be increased by implosion of hollow spheres, since the externally applied pressure acts over a larger volume[10].

Laser light has been focused to intensities greater than 10^{17} watts cm^{-2} (ref. 11). At such intensities the "light pressure" (momentum flux) is almost 10^8 atmospheres ($P \simeq I/c$ where I is the intensity, and c the velocity of light). Much higher pressures can be generated with intense light by a combination of ablation and implosion. The momentum flux (and pressure) associated with laser-driven ablation is much greater than that of the light for the same reason that matter-ejecting rockets

First ICF paper published in refereed journal. (1972)

COPDF 61-21

September 8, 1961

MEMORANDUM (Not published)

TO: J. Foster (Director, Livermore Laboratory)

FROM: J. Nuckolls

SUBJECT: Ideas for Symposium, Visiting Scientists

Following are "exciting" ideas I have recently considered which seem to merit further effort. They are obviously highly speculative . . .

(Sections on Strategic and Tactical weapons and BMD remain classified.)

THERMONUCLEAR ENGINE

The idea here is. . . to make the fusion analog of the cyclic internal combustion engine. DT or D is burned in a series of tiny contained explosions.

. . . . A problem is how to implode the DT to burn conditions without a relatively expensive pusher system . . . otherwise the fuel costs will be very high since the energy released from the burn of a mg of DT is worth <50 cents. It is proposed to use a radiation generator (a LASER system would be particularly advantageous here, because the energy could then be easily transferred via light – from the walls of the chamber to the DT) to make a pusherless implosion of a droplet of DT. . . calculations show that such an implosion and the subsequent tamperless burn is feasible for a droplet of DT weighing a few mg . . .

Possible applications for this engine are power production (Sherwood) or a thermonuclear rocket (fusion Rover).

First suggestions of laser-driven Thermonuclear Engine

(1961) – unpublished